

# **Human Factors Analysis and Layout Guideline Development for the Canadian Surface Combatant (CSC) Project**

*Final Report*

Paul McKay  
CMC Electronics

Curtis Coates  
CMC Electronics

Andrew Stewart  
CMC Electronics

Michael Perlin  
CMC Electronics

Prepared By:  
Esterline | CMC Electronics  
415 Legget Drive, PO Box 13330  
Ottawa, ON, Canada  
K2K 2B2  
Contractor's Document Number: N/A  
Contract Project Manager: Randy Meiklejohn, 613-592-7400 x2278  
PWGSC Contract Number: W7711-088136/001/TOR  
CSA: Dr. Wenbi Wang, Defence Scientist, 416-635-2000 x3063

The scientific or technical validity of this Contract Report is entirely the responsibility of the Contractor and the contents do not necessarily have the approval or endorsement of Defence R&D Canada.

## **Defence R&D Canada – Toronto**

Contract Report  
DRDC Toronto CR 2013-043  
April 2013

Principal Author

*Original signed by Paul McKay*

---

Paul McKay

Human Factors Specialist

Approved by

*Original signed by Dr. Wenbi Wang*

---

Dr. Wenbi Wang

Scientific Authority

Approved for release by

*Original signed by Dr. Joseph V. Baranski*

---

Dr. Joseph V. Baranski

Chair, Knowledge and Information Management Committee

© Her Majesty the Queen in Right of Canada, as represented by the Minister of National Defence, 2013

© Sa Majesté la Reine (en droit du Canada), telle que représentée par le ministre de la Défense nationale, 2013

## **Abstract**

---

These guidelines have been developed under contract to the DRDC Toronto Human Systems Integration (HSI) Section in support of the Canadian Surface Combatant (CSC) project. The goal of the project was to provide the Royal Canadian Navy (RCN) with a set of guidelines on analysis, design, and verification processes for effective room, equipment, and workstation layout in the bridge, operations room, machinery control room (MCR), and communications control room (CCR) in the yet to be designed CSC. The guideline development drew upon experience in the design of control spaces for complex systems, from existing guidance documents, and from interviews with domain experts.

## **Résumé**

---

La Section de l'intégration des systèmes humains (ISH) de RDDC Toronto a reçu le mandat, dans le cadre d'un contrat, d'élaborer des directives pour le projet des navires de combat de surface canadiens (NCSC). Ce projet avait pour but de fournir à la Marine royale canadienne (MRC) un ensemble de directives concernant les processus d'analyse de conception et de vérification utilisés pour aménager efficacement des espaces, de l'équipement et des postes de travail dans la passerelle, la salle des opérations, la salle de contrôle des machines et la salle de contrôle des communications des NCSC, qui ne sont pas encore construits. Pour créer les directives, nous avons puisé de l'information dans des documents d'orientation existants, fait appel à l'expérience d'entreprises privées en matière d'aménagement d'espaces de contrôle de systèmes complexes, et interrogé des spécialistes.

This page intentionally left blank.

## **Executive summary**

---

### **Human Factors Analysis and Layout Guideline Development for the Canadian Surface Combatant (CSC) Project: Final Report**

**Paul McKay; Curtis Coates; Andrew Stewart; Michael Perlin; DRDC Toronto CR 2013-043; Defence R&D Canada – Toronto; April 2013.**

#### **Introduction or background:**

The design of room layouts to effectively support communication between multiple personnel is a challenging problem; the challenges are particularly evident in the design of compartments for naval vessels where space and manpower are limited and the desired capabilities are complex. This project was initiated in support of the Canadian Surface Combatant (CSC) project, with the intent of developing guidelines on the analysis, design, and verification processes that should be used in the development of effective room layouts for Royal Canadian Navy (RCN) ships. The primary areas of focus for the project were the bridge, operations room, machinery control room (MCR), and communications control room (CCR) in the yet to be designed CSC; however, the guidelines could be applied to the design of any multiple-operator space in any RCN vessel.

#### **Results:**

The development of the guidelines drew upon material from existing guidance documents, industry experience in the design of control spaces for complex systems, and interviews with domain experts. The interviews with domain experts provided insight into the particular issues faced in developing room layouts for a naval application.

#### **Significance:**

Appropriate processes must be used throughout the development of room layouts in spaces that support multiple operators delivering complex capabilities. The cost of rework can become prohibitively expensive if errors are found late in the development of equipment. These guidelines provide the information required by a naval Project Management Office (PMO) to express the requirements of the process that should be followed and to verify that a contractor is following the process.

#### **Future plans:**

In the near term an application of the process in the CSC should be conducted and feedback from that design effort should be included in the guidance document to improve the process. The process could be applied to military platforms or spaces beyond the naval environment.

# Sommaire

---

## Human Factors Analysis and Layout Guideline Development for the Canadian Surface Combatant (CSC) Project: Final Report

Paul McKay; Curtis Coates; Andrew Stewart; Michael Perlin ; DRDC Toronto  
CR 2013-043 ; R & D pour la défense Canada – Toronto; avril 2013.

### Introduction ou contexte

L'aménagement de salles de façon à permettre une communication efficace entre de nombreuses personnes pose un problème de taille. Cela est particulièrement évident lorsqu'il est question de compartiments de navire militaire où la main-d'œuvre et l'espace sont limités et les capacités désirées sont complexes. Le projet dont il est question dans le présent document a été lancé pour appuyer le projet des navires de combat de surface canadiens (NCSC) avec l'intention d'établir des directives concernant les processus d'analyse, de conception et de vérification qui seront utilisés pour aménager efficacement les espaces dans les navires de la Marine royale canadienne (MRC). Nous nous sommes principalement attardés à la passerelle, à la salle des opérations, à la salle de contrôle des machines et à la salle de contrôle des communications des NCSC, qui ne sont pas encore construits. Cela dit, ces directives pourraient s'appliquer à l'aménagement de tout espace à opérateurs multiples de n'importe quel navire de la MRC.

### Résultats

Pour créer les directives, nous avons puisé de l'information dans des documents d'orientation existants, fait appel à l'expérience d'entreprises privées en matière d'aménagement d'espaces de contrôle de systèmes complexes, et interrogé des spécialistes. Ces derniers nous ont donné des éclaircissements sur les problèmes particuliers que l'on rencontre dans l'aménagement de compartiments de navire.

### Portée

Lorsqu'on configure des espaces à opérateurs multiples dotés de capacités complexes, il faut utiliser les bons processus. En effet, si l'on décèle des erreurs tard dans le processus de conception de l'équipement, cela peut entraîner des coûts prohibitifs de remise en fabrication. Ces directives donnent l'information dont un bureau de gestion de projets a besoin pour définir les exigences du processus qui devra être suivi et pour vérifier si l'entrepreneur se conforme à ce processus.

### Prochaines étapes

À court terme, nous comptons essayer le processus dans l'aménagement du NCSC pour ensuite ajouter les renseignements recueillis au document d'orientation afin d'améliorer le processus. Ce dernier pourrait être utilisé pour aménager des plateformes ou des espaces militaires autres que ceux de la Marine.

# Table of contents

---

Abstract .....	i
Résumé .....	i
Executive summary .....	iii
Sommaire .....	iv
Table of contents .....	iv
List of figures .....	viii
List of tables .....	ix
Acknowledgements .....	x
1 Introduction.....	1
1.1 Background .....	1
1.2 Purpose .....	1
1.3 Report content .....	1
1.3.1 High Level Guidelines.....	1
1.3.2 Design Process Guidelines .....	1
1.3.3 Design Process Verification Guidelines .....	2
1.3.4 PMO Implications.....	2
1.3.5 Compliance Matrix .....	2
2 High Level Guidelines .....	3
2.1 Intent.....	3
2.2 Background .....	3
2.3 Scope .....	3
2.4 Guidelines.....	3
2.4.1 Communications.....	3
2.4.2 Accessibility .....	3
2.4.3 Safety .....	4
2.4.4 Security .....	4
3 Design Process Guidelines.....	5
3.1 Intent.....	5
3.2 Introduction .....	5
3.3 Analysis .....	7
3.3.1 Requirements and Assumptions.....	7
3.3.2 Work Analysis .....	10
3.3.3 Communications Analysis .....	13
3.4 Layout Development .....	15
3.4.1 Communications.....	16
3.4.2 Accessibility .....	17
3.4.2.1 Ingress, Egress, and Traffic Flow .....	17

3.4.2.2	Maintenance .....	18
3.4.3	Safety .....	19
3.4.4	Security .....	20
3.4.5	Design Trade-Offs .....	21
3.5	Layout Evaluation .....	22
3.5.1	Verification .....	23
3.5.2	Validation .....	25
4	Design Process Verification Guidelines .....	27
4.1	Intent.....	27
4.2	Analysis .....	27
4.2.1	Requirements and Assumptions.....	28
4.2.1.1	Reference Documents .....	28
4.2.1.2	Intended Functions.....	28
4.2.1.3	Room Size and Features.....	29
4.2.1.4	Manning Concept.....	29
4.2.1.5	Equipment.....	29
4.2.1.6	Ingress and Egress.....	31
4.2.1.7	Anthropometric Data Sources .....	31
4.2.2	Work Analysis .....	33
4.2.3	Communications Analysis .....	37
4.2.3.1	Communication Types .....	37
4.2.3.2	Communication Metrics.....	39
4.3	Layout Development .....	40
4.3.1	Communications .....	40
4.3.2	Accessibility .....	40
4.3.2.1	Use of Anthropometric Data .....	41
4.3.3	Safety .....	42
4.3.4	Security .....	43
4.3.5	Design Trade-Offs .....	43
4.4	Layout Evaluation .....	43
4.4.1	Verification .....	43
4.4.2	Validation .....	44
5	PMO Implications.....	46
5.1	Intent.....	46
5.2	High Level Requirements.....	46
5.2.1	Communications .....	46
5.2.2	Accessibility .....	47
5.2.3	Safety .....	48
5.2.4	Security .....	48
5.3	Analysis .....	48
5.3.1	Work Analysis .....	48



5.3.2	Communications Analysis .....	49
5.4	Layout Development .....	49
5.4.1	Notional Layouts .....	49
5.4.2	Test Layouts.....	50
5.5	Layout Evaluation .....	50
6	Conclusion .....	51
6.1	Future work .....	51
References .....		52
Annex A Example Compliance Matrix.....		54
List of symbols/abbreviations/acronyms/initialisms .....		60
Distribution list.....		<b>Error! Bookmark not defined.</b>

## List of figures

---

Figure 1: Tailored ISO 11064 Room Layout Design Process. ....	6
Figure 2: Iterative Room Layout Process. ....	7
Figure 3: Sample Source / Receiver Relationships. ....	14
Figure 4: Cooper-Harper Rating Scale. ....	36
Figure 5: Sample Receiver Functions – Distance (RD) and Angular (RA). ....	39
Figure 6: Structural Anthropometric Measurement. ....	42
Figure 7: Functional Anthropometric Measurement. ....	42

**List of tables**

---

Table 1: Sample Bridge and Ops Room Equipment Lists..... 30

Table 2: Sample CCR and MCR Equipment Lists..... 31

## Acknowledgements

---

The research team would like to acknowledge the support provided by PMO CSC (Capt Swann) for arranging Subject Matter Expert (SME) sessions to assist in the development of the guidelines. The team would also like to acknowledge the support of the SMEs that participated:

- CPO2 Bishop
- LCdr Blanchard
- CPO1 Burke
- CPO1 Darragh
- LCdr Gowigati
- LCdr Malek
- LCdr Schlosser

# **1 Introduction**

---

## **1.1 Background**

The design of room layouts to effectively support communication between multiple personnel is a challenging problem; the challenges are particularly evident in the design of compartments for naval vessels where space and manpower are limited and the desired capabilities are complex. This project was initiated in support of the Canadian Surface Combatant (CSC) project, with the intent of developing guidelines on the analysis, design, and verification processes that should be used in the development of effective room layouts for Royal Canadian Navy (RCN) ships. The primary areas of focus for the project were the bridge, operations room, machinery control room (MCR), and communications control room (CCR) in the yet to be designed CSC; however, the guidelines could be applied to the design of any multiple-operator space in any RCN vessel.

## **1.2 Purpose**

The purpose of this report is to provide control room layout guidance to the CSC Project Management Office (PMO). It is intended to provide the naval operators and engineers with a process to follow to ensure the ship's designers and builders have adequately positioned the operators and equipment within designated compartments in the ship. The work was initiated to identify layout requirements and generate design guidelines for key control spaces in the CSC. More specifically, this work produced a set of "best practice" design guides for the layout of control spaces based on operator task and information exchange requirements. The report is not a "how-to" guide that explains all the detailed processes that could be followed in the design of a space and it is not a literature review of Human Factors techniques related to room layout.

## **1.3 Report content**

This report contains room layout guidance along with a compliance matrix. Each section starts with a statement on intent for that section. The report contains the following sections:

### **1.3.1 High Level Guidelines**

The high level guidelines provide design criteria for naval ship room layouts. This section positions the detailed guidelines which are contained in the subsequent sections.

### **1.3.2 Design Process Guidelines**

The design process guidelines provide a description of a room layout design process, tailored specifically for the naval context. This guidance is provided to allow a designer to create a layout that meets the high level guidelines described the previous section.

### **1.3.3 Design Process Verification Guidelines**

This section provides additional details about the process described in the design process guidelines section. It will allow an evaluator to assess whether the process was followed appropriately and whether the developed layout meets the high level guidelines described in the high level guidelines.

### **1.3.4 PMO Implications**

This section provides a naval PMO with information regarding anticipated schedule and SME requirements associated with the processes described in the document. This information is provided in sufficient detail to assist the PMO in the planning of timing and duration of availability required from RCN personnel to act as SMEs to provide inputs to the process and/or as evaluators to assess the contractor deliverables.

### **1.3.5 Compliance Matrix**

This Annex to the report contains an example compliance matrix for the validation of the room layout design process.

## **2 High Level Guidelines**

---

### **2.1 Intent**

The intent of the high level guidelines is to provide design criteria for naval ship room layout that position the detailed guidelines of the following sections, in a similar fashion to how high level requirements in a Statement of Requirements (SOR) position the low level requirements of a project.

### **2.2 Background**

Effective design of ship workspaces (e.g., bridge, operations room, Machinery Control Room (MCR), and Communications Control Room (CCR)) must account for the human components (strengths and limitations), their roles within the work organization, and their performance in operational systems. The guidelines that follow contribute to this recognition and to effective, efficient, and safe room configurations.

### **2.3 Scope**

These guidelines apply to the layout of compartments intended for use in the operation of Canadian warships where multiple operators are required for any expected operational condition.

### **2.4 Guidelines**

The compartment must be designed so that the operators, in combination with the installed systems and equipment, can safely and efficiently perform all of the functions required considering all operating conditions in the space. The layout of the compartment should follow the guidelines provided in the following subsections (2.4.1 through 2.4.4). In some cases, the guidance described in these subsections may be in conflict; therefore, the relative importance of each guideline must be considered in the context of the intended functions (i.e., the intended purpose of the space, technology, or person) to determine the appropriate design trade-offs.

#### **2.4.1 Communications**

- a. The layout should support all inter-personnel communications required to accomplish the intended functions of the space.
- b. The layout should support all personnel-equipment communications required to accomplish the intended functions of the space.

#### **2.4.2 Accessibility**

- a. The layout should be designed to accommodate the expected user population.

- b. The layout should be designed to facilitate efficient, unobstructed movement of operators within the space.
- c. The layout should provide sufficient ingress and egress routes (e.g. numbers of personnel, types of equipment, emergency time requirements) for all operators in all potential configurations.
- d. Movement paths within the space, including ingress and egress routes, should be situated to minimize operator distraction resulting from traffic flow within the room.
- e. The layout should provide access for all required maintenance.
- f. The layout should provide access for all required husbandry activities.

### **2.4.3 Safety**

- a. The layout should be designed to protect personnel from injury during all operating conditions.
- b. The layout should be designed to accommodate the requirements of naval firefighting and damage control.
- c. To the extent practicable, the layout should be designed to prevent crew discomfort resulting from:
  - i. Noise;
  - ii. Vibration;
  - iii. Climate;
  - iv. Lighting; or
  - v. Ship motion.

### **2.4.4 Security**

- a. The layout should be designed to accommodate all security requirements of the space, such as:
  - i. Control of access to the space; and
  - ii. Control of access to specific information within the space.



## **3 Design Process Guidelines**

---

### **3.1 Intent**

The intent of this Section is to provide a description of a room layout design process, tailored specifically for the naval context. This guidance is provided to allow a designer to create a layout that meets the high level guidelines described in Section 2 for any compartment in a Navy ship. As such, this Section contains naval-specific details where applicable, but does not contain information specific to a single space or compartment within a ship. Compartment-specific examples are used, however, to illustrate generic elements of the process.

The guidance material described in this Section (3), and the following Section (4), is derived from extensive industry experience in room layout design, industry guidance documents, and Human Factors Engineering (HFE) best practices.

### **3.2 Introduction**

The room layout design process described in this Section (3) is largely based on the methodology described in ISO 11064 – Ergonomic design of control centers [1], with modifications to support the specific requirements for the layout of naval control centers. The overall structure of this tailored design process (illustrated in Figure 1, below) can be broken down into three major, overlapping segments:

- a. Analysis (see Section 3.3),
- b. Layout Development (see Section 3.4), and
- c. Layout Evaluation (see Section 3.5).

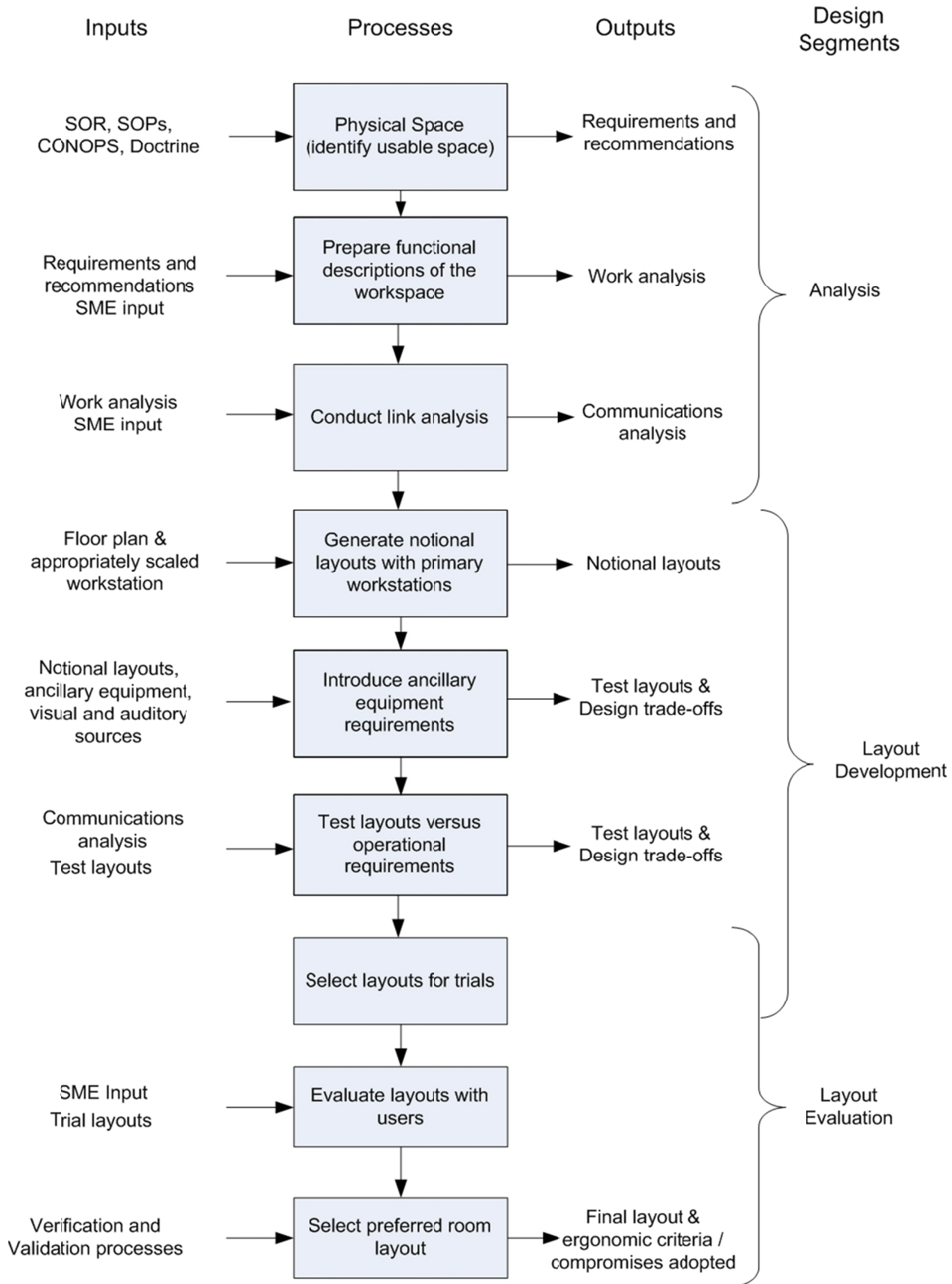
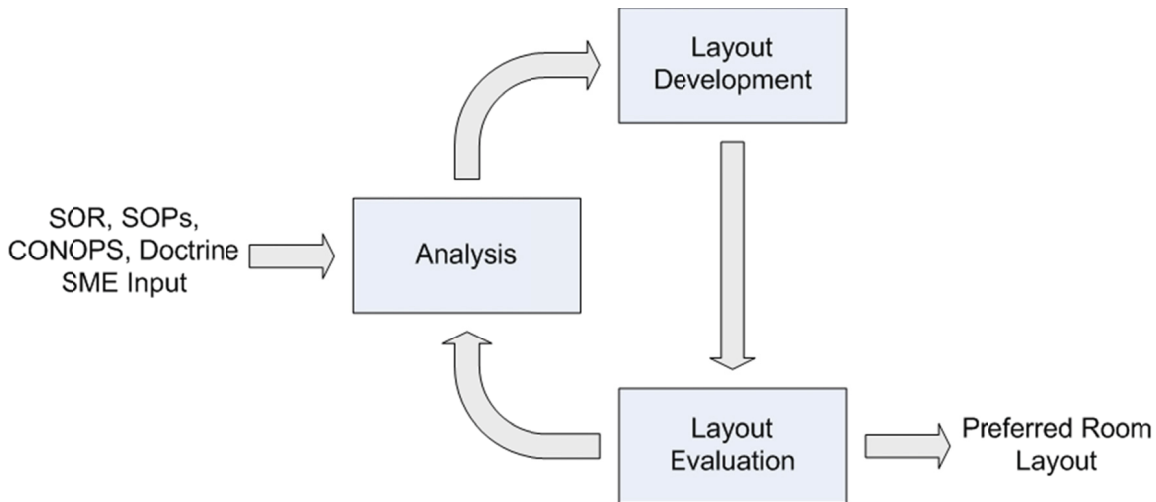


Figure 1: Tailored ISO 11064 Room Layout Design Process.

It is important to note that the overall design process illustrated in Figure 1 and detailed in Sections 3.3 through 3.5 is an iterative process; that is, as new or updated information is obtained throughout the process, the earlier stages of the process should be re-visited to ensure that any effects from this information are captured. For example, information obtained during layout development could necessitate updating the analysis, while information obtained during layout evaluation could result in changes to the developed layouts or to the analysis. Refer to Figure 2 for an illustration of the iterative nature of the process.



*Figure 2: Iterative Room Layout Process.*

### 3.3 Analysis

As illustrated in Figure 1, the analysis process employed to collect the data for use in layout development and evaluation includes a variety of elements. These elements range from the development and validation of the intended functions of the space and other relevant assumptions (detailed in Section 3.3.1) to the detailed analysis of the intended functions of the space (described in Section 3.3.2) and, the last step in analysis, the communications and information flow required to accomplish these functions (detailed in Section 3.3.3).

One common factor that applies to all stages of the analysis process is that Subject Matter Expert (SME) input is required to ensure that concerns specific to the operational environment are appropriately considered and captured.

#### 3.3.1 Requirements and Assumptions

At the beginning of the analysis process, a number of the characteristics of the space being analysed should be largely finalized and recorded to be used as inputs to the room layout process. These characteristics include:

- a. **Operational Conditions.** It is essential to know under what conditions the crew is expected to operate within the spaces being designed. There are several possible ways of categorizing these operational conditions; for the purposes of layout design, the four categories (applicable

to warships) defined in the Safety of Life at Sea (SOLAS) submission template for major refits and new builds [2] provide a useful starting point. These four categories, with definitions adapted to generic room layout, are:

- i. Normal – When all shipboard systems and equipment related to the primary functions of the space operate within design limits, and weather conditions or traffic do not cause excessive operator workloads.
  - ii. Irregular – When external conditions cause excessive operator workloads requiring professional assistance within the space.
  - iii. Abnormal – When internal technical system failures require operation of basic back-up systems or when they occur during an irregular operating condition, or when the officer of the watch becomes unfit to perform his duties and has not yet been replaced by another qualified officer.
  - iv. Emergency – When failure of internal ship systems not affecting the ability of navigation or manoeuvring, or fire incidents occur which need to be controlled and managed from the space being designed.
- b. **Intended Functions.** The top-level intended functions of the space will need to be identified to serve as the starting point for the work analysis described below. This is an extremely important step in the design process as it is not typically practical for warships to provision a significant amount of space for future growth in capability. The primary sources for the identification of the intended functions of the space should be the applicable defense policy/strategy documents, the SOR for the ship, and the Concept of Operations (CONOPS) documents for the ship. If these documents are not all available during the initial definition of the requirements and assumptions, the intended functions should be re-visited when the applicable documents become available. In addition to the specific operational functions, it is expected that, at minimum, the following support functions will need to be considered in each space:
- i. Firefighting and Damage Control;
  - ii. Maintenance;
  - iii. Force Generation (e.g., training and drills);
  - iv. Evaluation or Assessment (e.g., Sea Training); and
  - v. Husbandry.
- c. **Room Size and Features.** Any limitations on the size and/or shape of the room should be recorded; if no limitations have been defined, layout designs can still be created and can actually be used to develop requirements for the size and/or shape of the space. If the room already exists or has been designed, the construction features of the room should be recorded, including elements such as the placement and size of doors, windows, support pillars, and ventilation ducts/vents.

- d. **Manning Concept.** The notional manning concept of the space, describing the number and type of personnel expected to carry out the intended functions, does not necessarily need to have been determined in the early stages of the analysis; however, initial assumptions may be required to facilitate certain types of work analysis (as described in Section 3.3.2). In order to proceed with the communications analysis (Section 3.3.3), a notional manning concept will be required. An important consideration when describing the notional manning concept of the space is the variability of the manning level; some spaces have a dynamic manning level that is highly dependent on the operational condition and degrees of readiness of the ship, while others are relatively stable in almost all conditions. The analysis should consider all potential manning levels to ensure that the layout of the space supports all operational conditions.
- e. **Required Equipment.** The equipment required to carry out the intended functions of the space should be identified. These equipment requirements should include items that may not be included in the initial ship configuration (i.e., items that will be provisioned for but not installed) as well as any additional equipment required to support future capability growth (e.g., extra workstations). Examples of the types of equipment that may be required include:
- i. workstations<sup>1</sup>,
  - ii. shared information systems (e.g., large common displays, stateboards),
  - iii. communications equipment (e.g., headsets, SHINCOM telephones), and
  - iv. operation-specific ancillary equipment (e.g., ship gyro, inclinometer, veto panels).

Relevant data such as physical size/shape and maintenance requirements should be recorded for each piece of equipment.

- f. **Ingress/Egress Requirements.** The ingress/egress requirements of the space should be identified. These requirements should include considerations such as the number of entrances and/or exits required and the number of independent ingress/egress routes for each operator within the space.
- g. **Population Anthropometric Measures.** Relevant anthropometric data for the user population will be required to ensure that accessibility requirements are appropriately considered. Refer to Appendix B of MIL-STD-1472G [3] for sample anthropometric data tables; note that these data tables are very comprehensive, and likely contain more measurements than will be required for use in the room layout design process. The appropriate anthropometric dimensions, and type of anthropometric measurement (structural or functional), will need be identified for each design problem during the layout process. It should also be noted that the tables in MIL-STD-1472G are based on unclothed

---

<sup>1</sup> It should be noted that although workstation design is not covered by this document, it is a complex design task and should be carefully considered to ensure that appropriate designs are created. As the workstation designs are a key element of the overall room layout, the design effort to create them should occur ahead of or in parallel with the room layout design process. For further information regarding workstation design, refer to MIL-STD-1472G [3], Sanders & McCormick [4], and ISO 9241 [5].

measurements, which mean that they disregard an important consideration: accommodation for clothing and any applicable operational or protective equipment. To ensure that the final layout design provides acceptable accessibility, this consideration will need to be accounted for in the population anthropometric data.

It is recognized that some of these characteristics will not have been finalized at the stage of ship design when room layouts are being created. For these characteristics, working assumptions should be agreed upon and recorded in order to proceed with the analysis, and re-visited throughout the design process to ensure any changes are accounted for.

### **3.3.2 Work Analysis**

The work that will be performed in the space being designed must be captured using a method that ensures complete coverage of all activities, allows for sufficiently detailed analysis to determine the communication requirements of the space, and facilitates validation by SMEs who may not be experts in work analysis. There are a variety of work analysis techniques that meet these criteria and could be used to conduct the analysis in support of layout design; examples include Mission, Function, Task Analysis (MFTA) [6], Work Domain Analysis (WDA) [7-8], and Hierarchical Goal Analysis (HGA) [9]. Further discussion of work analysis and other techniques can be found in Wilson & Corlett [10], MIL-HDBK-46855A [6], and NATO STANAG 3994 [11].

For any of the work analysis techniques, the starting point for the analysis should be the intended functions of the space as identified in Section 3.3.1, Item b. When considering the specific operational functions of the space, the information that should be recorded for each function (or sub-function, if applicable) will vary depending on the nature of the function itself; however, the following list provides examples of the types of information that are typically required:

- i. The expected frequency of occurrence of the function (note that this would include the identification of functions that are carried out continuously, i.e. watchstanding);
- ii. The importance of the function to the overall success of the space;
- iii. Any operational links between the function and other functions/sub-functions;
- iv. Information flow and communications required to complete the function (note that for functions that require shift changes/watch turnover, the communications required to accomplish the turnover should be specifically considered because of the additional information exchange required);
- v. Any equipment or support material necessary to accomplish the function; and
- vi. Storage space requirements (if applicable) for the necessary equipment or support material.

When identifying the information flow and communications required for a function, specific attention should be paid to whether the function requires operator awareness of the ship's

orientation (e.g., relative to a compass heading, a contact, or an environmental feature) or of the operator's location or orientation relative to the ship (e.g., when supervising firefighting or damage control operations). The requirement for this type of awareness has a specific impact on the positioning of operators within a space (see Section 3.4.1 for further detail).

Some or all of the equipment required to accomplish the function may have already been identified under the requirements and assumptions for the analysis (see Section 3.3.1, Item e). For equipment not previously identified, information about the equipment should be recorded in the same manner as for the items in Section 3.3.1, Item e.

Storage space requirements for a function can generally be broken down into four categories:

- i. Immediate personal storage – Operators typically require some amount of storage space at or very close to their work location for personal items and frequently used support materials (e.g. a war bag).
- ii. Lower priority personal storage – Additional storage space is often required within the compartment for bulkier and/or less frequently needed personal items such as clothing (e.g. wet weather gear) as well as lower priority support materials such as Personal Protective Equipment (PPE).
- iii. Document storage – Sufficient space should be provided to store all required documentation associated with the functions of a compartment.
- iv. Function-specific storage – In addition to the storage requirements in i. through iii. above, storage space may be required for equipment or materials specific to a function of the compartment. Examples of this from existing warships include the lock out/tag out locker in MCR/HQ1 and the NAVCOM equipment locker on or near the bridge.

In addition to the specific operational functions of the space, the support functions listed in Section 3.3.1, Item b, also need to be considered during the work analysis. Examples of the types of information that should be recorded when considering these support functions are provided below. It should be noted that some of the recommended information to be recorded, related to both the specific operational functions (above) and the support functions (below), is required primarily for the purposes of design trade-off analysis. This information, such as the expected frequency or importance of a maintenance action (see b. i. and ii. below), may not be required if the layout is able to accommodate all functions with few (or no) trade-offs.

- a. **Firefighting and Damage Control.** To ensure that the intended firefighting and damage control techniques for the space being designed are accommodated, the following information should be recorded:
  - i. The intended technique for firefighting - CO2 flood, the use of attack teams, or other method;
  - ii. Specific damage control concerns; and

- iii. Any requirement to activate firefighting or damage control systems from inside or outside the compartment.
- b. **Maintenance.** For all maintenance actions that will be carried out within the space being designed, the following information should be recorded:
  - i. The expected frequency of the maintenance action;
  - ii. The importance of the maintenance action for continued operation of the equipment being maintained;
  - iii. The estimated time required to complete the maintenance action;
  - iv. Whether the maintenance action can be carried out during ongoing operations;
  - v. If the maintenance action can be carried out during operations, any impact(s) on the ongoing operations while the maintenance action is taking place;
  - vi. The number of maintainers required to carry out the maintenance action;
  - vii. Communications required for the maintenance action;
  - viii. Any tools or equipment (spares, etc) required for the maintenance action;
  - ix. Storage space required for the maintenance action; and
  - x. The maintainer posture(s) required while conducting the maintenance action.
- c. **Force Generation.** The function of force generation can be considered within a space either as a support function (i.e., a high level function of the space) or as a sub-function of the operational functions of the space. In either case, the following types of information should be recorded:
  - i. Number and type of personnel providing training/supervision;
  - ii. Number and type of personnel being trained/supervised;
  - iii. Communications required between trainer(s) and trainee(s);
  - iv. Additional workspace required if trainer and trainee are working in close proximity; and
  - v. Additional equipment required to support force generation (e.g. spare workstations).
- d. **Evaluation or Assessment.** To ensure evaluation staff (including Sea Training) can be appropriately considered in the layout of the space, the following information should be recorded:



- i. Which operational and/or support functions can be ongoing concurrently with sea training;
  - ii. Number of evaluation personnel observing the ongoing operations;
  - iii. Information requirements for each of the sea training personnel (i.e., which operator(s) and/or equipment are the sea training personnel observing).
- e. **Husbandry.** For the husbandry activities that will be carried within the space being designed, the following information should be recorded:
  - i. Whether the husbandry activity can be carried out during ongoing operations;
  - ii. If the husbandry activity can be carried out during operations, any impact(s) on the ongoing operations while the husbandry activity is taking place;
  - iii. The number of personnel required to carry out the husbandry activity;
  - iv. Communications required for the husbandry activity;
  - v. Any tools or equipment required for the husbandry activity;
  - vi. Storage space required for the husbandry activity; and
  - vii. The personnel posture(s) required while conducting the husbandry activity.

The information recorded during the work analysis can then be used to inform the communications analysis (detailed in Section 3.3.3) and the development of notional room layouts (described in Section 3.4).

### 3.3.3 Communications Analysis

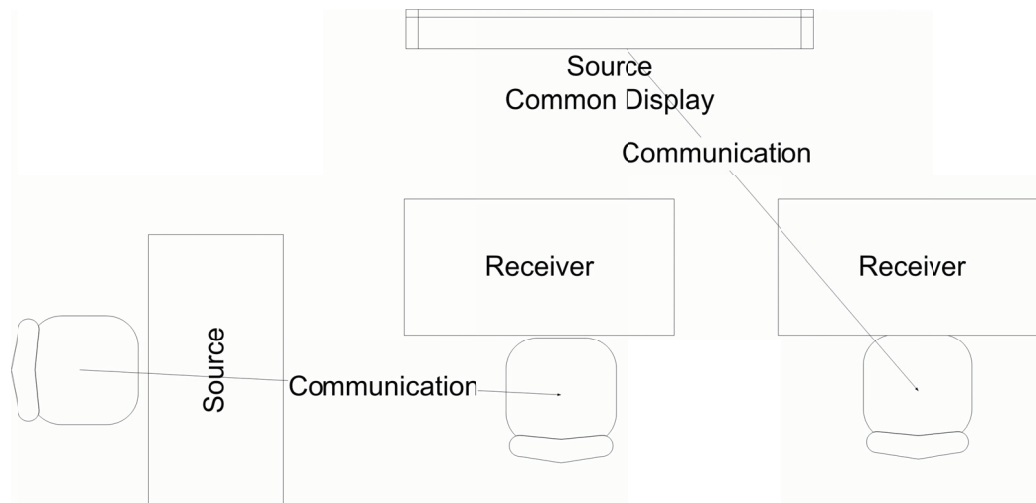
All interactions between components in a system (human or machine) are defined as links [6]. Generally, links can be subdivided into three classes: communication (auditory or visual); control (from human to machine); and movements (eye, body, hand, or foot). Communication links comprise information interactions whether they are human-machine, machine-machine or human-human. Link analysis can be used by the analyst as an aid in developing an optimal layout for a work area, workstation, or control/display panel.

MIL-HDBK-46885A [6] explains that link analysis helps in the design optimization process by providing HFE practitioners with information on the number, sequence, and types of interactions among personnel and equipment, and their relative location. In order to fully understand the requirements of a space the HFE practitioner needs to remember that other factors (e.g., sensory modality, message priority) could also influence what is the optimal layout.

Before beginning the communications analysis for a space, a work analysis (Section 3.3.2) must be conducted in order to identify the information flow and communications required to meet the intended functions of the space. It is only once these requirements have been defined that the

detailed analysis of the communications within the space can commence. Communications for the support functions listed in Section 3.3.1, Item b (firefighting and damage control, maintenance, force generation, evaluation or assessment, and husbandry), need to be considered if communication requirements were identified for them as part of the work analysis.

A thorough understanding of the communication requirements of a space, and the different types of communication that can satisfy these requirements, is critical to ensuring that operators can effectively complete their tasks and accomplish the intended functions of the space. Communications can be considered to occur between operators within the space or between an operator and a piece of equipment (e.g., visual observation of displays or ancillary equipment, auditory input from speakers). All communications occur between a source and a receiver, who are linked by the communication that takes place. Refer to Figure 3 for sample source / receiver relationships in the context of a partial room layout.



*Figure 3: Sample Source / Receiver Relationships.*

The effectiveness or quality of a communication link is dependent on the characteristics of both the source and receiver of the communication. It is therefore important to clearly define the source and receiver for each communication in a manner that allows the characteristics of both ends of the communication to be captured. The definition of source and receiver can be dependent on the communication type, or can be defined using a rule that allows a consistent determination of the source and receiver for all communication types (e.g., the operator allocated responsibility for the function/task/goal is the receiver).

When analyzing the communication links defined between each source and receiver within the space, the following considerations should be taken into account:

- a. **Communication Types.** Communication, for the purposes of link analysis and layout design, includes all potential modalities (e.g., visual, auditory, tactile). When analyzing operator-machine communication, it is typically straightforward to determine which modality or modalities will be used. When dealing with operator-operator communications, however, the modes can often become mixed depending on the purpose of the communication taking place. For example, when the communication involves providing direction to another operator in

person, there is an obvious auditory component (i.e., the voiced direction), but there is also a visual component involved in determining whether the direction was processed and understood. Communications that serve a different purpose may require a greater or lesser emphasis on a given modality. As a result, the analysis should not only consider the modality of communication, but also the type (or purpose) of such communication. These communication types must be defined as part of the analysis and confirmed by SMEs.

- b. **Communication Importance.** Naval ships are required to deal with unexpected or infrequent occurrences with potentially severe consequences in addition to day to day tasks. For this reason, the primary factors that should be considered when determining the importance of a communication link are the expected frequency of the communication and the consequences of a failure in the communication. These two factors can be captured separately or combined into a single measure of importance, but both factors should be considered to ensure that the space can effectively support both ongoing and crisis response functions.
- c. **Angular and Distance Constraints.** In order to support an analysis of communication effectiveness in a notional room layout, the angular and distance requirements and limitations must be determined for each type of communication. For example, basic auditory communication between operators is typically highly effective within a threshold distance but falls off rapidly outside that distance. The angular component also typically has a noticeable effect; generally, the communication will be most effective if the source and receiver directly face one another and somewhat less effective (but still possible) as the angular alignment moves in either direction away from the center point. The threshold distance and effects of angular alignment vary depending on the communication type and the space under consideration and should be established and validated with SME input.
- d. **Noise Masking and Distraction.** The communication analysis must also consider noise interference caused by the masking effect of noise on speech. Depending on the ambient level of background noise operators may have to be closer to one another to have conversations or speakers may need to be set to a higher volume to allow for receipt of information. This effect can either be factored into the angular and distance constraints described above or modeled as a separate effect.

The effect of layout on communications and the need to support communications as a layout design factor are critical to development of an effective space. The communication and subsequent link analysis performed must be applied in a rigorous and deliberate manner. Each communication link must be modelled and the effects of all other features (e.g., other operators, fitted equipment, air ducts, passageway, and lights) must be considered in each link. The contractor should employ visual tools such as link diagrams to support the development and review of the communication analysis.

### 3.4 Layout Development

After completing the analyses described in Section 3.3, the next step in the room layout process is to begin developing notional room layouts. These layouts should account for the communication,

accessibility, safety, and security requirements of the space, as explained in the following subsections (3.4.1 through 3.4.4).

As previously mentioned, some of these requirements may cause conflicting demands on the layout of the space; optimization of the layout is therefore conducted through a design trade-off process that involves creating different notional layouts to reflect the different trade-offs under consideration. Guidance regarding useful criteria to be considered in assessing design trade-offs is provided in subsection 3.4.5.

Once several notional room layouts have been created, they should then be validated against the operational requirements of the space that were captured during the analysis process. This validation process should include SME input, and is described in further detail in subsection 3.5.1. In order to select a preferred layout solution, the validated notional layouts should then be subjected to a more detailed, performance-based layout evaluation process (as described in Section 3.5.2).

### **3.4.1 Communications**

The basis for evaluating the effectiveness of a layout is its ability to support the communication requirements of the operators. Communication is therefore the primary driver in determining the relative placement of operators and equipment within the space, driven by functional and operational links. The importance ratings (for functions/tasks/goals and communication links) collected in the communications analysis should be combined with the quality of each communication afforded by the layout to calculate the quality of overall communication within the control room. Primarily, the analysis is concerned with the communications occurring within the confines of the room being designed. Information or data entering or leaving the compartment are generally included only if they occur through common displays/loudspeakers.

Notional layout designs should be based on communications analysis, SME input, and best practices from guidance documents. For example, Annex A of ISO 11064 [1] provides a number of conceptual workstation groupings based on the presence or absence of supervisors and common displays. A rating for each of these groupings is also provided based on the best practices Feature Set from the ISO, which includes: Sharing Workstation Equipment; Sharing off-workstation displays; Direct eye contact; Verbal communication; Low noise interference; Message passing; Collection and delivery of paperwork; Standing in for supervisor; Operator training by supervisor; and Equipment access for maintenance. Each item in the feature set should be ranked regarding its importance to the work space and cross referenced with the conceptual workstation groupings provided in the ISO.

Notional room layouts can then be created based on the workstation groupings that best support the requirements of the work space. When placing these workstation groupings within the space, specific consideration should be paid to the direction that each operator will be facing relative to the ship's orientation; based on interviews with Royal Canadian Navy (RCN) personnel, the general preference is for operators to face forward, particularly for functions where awareness of ship or operator orientation is important (as identified in the work analysis). It is advisable to generate multiple notional layouts to provide differing starting points for evaluation.

The assessment of the notional and test layouts should be based on the approved communication metrics developed with input from SMEs and the application of the communications analysis. During the design all receivers and sources of communications should be placed in the test layout.

### 3.4.2 Accessibility

The primary considerations related to physical accessibility in a room layout are related to the size and shape of the personnel and equipment within the space. While these considerations have a significant impact on micro-level layout decisions (e.g., how far apart do two pieces of equipment need to be to allow accessibility for maintenance), they tend to have much less impact on the macro-level decisions related to the relative layout of operators and equipment within the space (e.g., does the CO's seat need to be located close to the chart table). These macro-level functional accessibility considerations are generally accounted for in the communications requirements and integrated into the notional layouts as described in Section 3.4.1, above.

In general terms, the goal of considering physical accessibility within the space is to ensure that all operators in the expected user population have sufficient physical access to perform all tasks that could be required of them in the space. This typically means examining the 'worst-case scenario' for the task under consideration (e.g. for an ingress or egress route, sufficient space must be provided for the largest operator or operators with the bulkiest clothing/PPE and largest equipment that may be required). Guidance for addressing specific accessibility concerns are provided in the following subsections (3.4.2.1 and 3.4.2.2).

#### 3.4.2.1 Ingress, Egress, and Traffic Flow

The primary accessibility aspect to be considered for the ingress, egress, and traffic flow routes within the space is the physical size and clearance required for each route. The size (typically height and width) required for an ingress, egress, or traffic flow route can be determined from:

- a. **Intended Uses of Route.** The intended use of the route must be identified; for example, a route that is used for concurrent ingress and egress will require space for two operators to pass side-by-side, and a route that supports maintenance personnel will require space for any applicable maintenance equipment or spares.
- b. **Anthropometric Data.** The anthropometric data of the user population (see Section 3.3.1, item g) is used to determine the space requirements for the personnel using the route. The typical measurements used in considering walking routes are the height and shoulder breadth of the population; note that these measurements must account for clothing, PPE, and carried equipment if applicable.
- c. **Equipment Size.** If any equipment is required to be moved along the route (e.g., for maintenance purposes), the size of this equipment must be accounted for in the space provided for the route.
- d. **Clearance Space.** To ensure that the routes are usable for their intended purpose, clearance space is required in addition to the space required for personnel and/or equipment. This clearance space allows for comfortable movement and helps to account for potential snagging

hazards on the route. For example, for a route intended to allow operators to pass side-by-side, it would not be sufficient to define the required width as twice the maximum expected shoulder width of the population, even if clothing and equipment are included in this measurement. Additional space must be added to allow for distance between the two operators and between each operator and the side of the route.

Based on this data, the required size of the route can be determined by adding the appropriate anthropometric, equipment, and clearance measures. However, the required physical size is not the only relevant consideration when considering ingress, egress, and traffic flow routes within the space; the following factors should also be taken into account:

- a. **Potential for Operator Distraction.** In order to reduce the potential for operator distraction resulting from traffic flow within the space, the traffic flow routes should provide sufficient clearance from all identified operator positions in the space. The determination of how much clearance is sufficient should be informed by consultation with SMEs.
- b. **Ship Traffic Routes.** If the layout design will include multiple entrances/exits, consideration should be given to the location and orientation of the compartment within the ship to ensure that the ingress/egress routes within the compartment do not become passageways for traffic within the ship.
- c. **Access to Entrances and Exits.** When it is anticipated that an operator will be required to leave the space or communicate with transient personnel on a regular basis, it is recommended that the operator's position in the space be located close to a main entrance. This placement can increase work efficiency and reduce the potential for distraction of other operators as described above. For example, the ORO may leave the Operations Room on a regular basis to go to the bridge and communicate in-person with the CO, and the Engineering Officer of the Watch may require frequent in-person communication with the engineering roundsmen; these positions should be located close to an entrance (though still with enough clearance from the ingress/egress route to avoid distraction as described above).

#### 3.4.2.2 Maintenance

To ensure that accessibility for maintenance is appropriately considered in the proposed layout, it is necessary to determine the space requirements associated with each maintenance action. These space requirements can be constructed based on the data recorded as part of the analysis process described in Section 3.3. In particular, the space requirement for a given maintenance action can be determined from:

- a. **Location of the maintenance action.** The location of the maintenance action will need to be identified as it will determine where the applicable space for maintenance must be provided. Where possible, the location should be specified such that it can be moved around the space if the notional layout of the space is changed. For most maintenance actions, it is expected that the location of the maintenance will be linked in a specific orientation to the piece of equipment being maintained (e.g., if a workstation is maintained from the opposite side to which it is operated, the maintenance space must be provided on the appropriate side of the workstation).



- b. **Space required for maintainer(s).** The space required for the maintainer or maintainers is based on the number of maintainers involved, the posture(s) required for the maintenance action (e.g., standing, sitting, crouching), and the anthropometric data for the user population. All identified postures for each of the maintainers should be considered to determine the maximum potential space requirement.
- c. **Space required for tools/equipment, if applicable.** If specific tools or equipment are required to complete the maintenance action, the space required for these items will also need to be considered. This may impact the space requirement while conducting maintenance (e.g., if the maintainer(s) need access to a tool cart while performing the action) but may also impact ingress/egress requirements for the space (e.g., if the maintenance action requires a large component to be replaced, ingress/egress routes must be of sufficient size to allow the replacement component to be brought to the maintenance location and to allow the original component to be removed from the space).

Once the location and the total space required for each maintenance action have been determined, these space requirements should be included in the notional layout designs.

### 3.4.3 Safety

There are a variety of safety concerns that should be considered when creating a room layout in order to ensure that the operators in the space are able to complete their tasks safely and comfortably. At minimum, the following potential safety concerns should be specifically addressed in the layout design:

- a. **Workplace Hazards.** The room layout should be designed to reduce or eliminate hazards that could cause operators moving around the space to slip, trip, or snag. Handrails, guardrails, and bracing points should also be provided as applicable to reduce likelihood of falls. All equipment and features provided for this purpose should be considered when designing the ingress, egress, and traffic flow routes in the space (see Section 3.4.2.1). Refer to MIL-STD-1472G [3] for further information on workplace hazards and design techniques for mitigation.
- b. **Noise.** Noise levels within the space should be maintained within appropriate levels; refer to Table XXVI of MIL-STD-1472G [3] for noise level guidance. Additionally, the location of any non-hazardous noise-causing equipment within the space should be considered relative to operator positions to ensure that operator communications and task performance are not affected. The masking effect on noise on speech is well documented in Chapter 10 of the Handbook of Control Room Design and Ergonomics [12]. To this end, such pieces of equipment should be considered as part of the communications analysis to assess their effect on operator communications.
- c. **Vibration.** Any vibration-causing equipment required within the space should, if possible, be located sufficiently far away from operator positions to prevent nuisance vibrations from reaching personnel. Should this not be possible, alternate means of reducing vibration (e.g., isolation mounting) should be considered.

- d. **Climate.** It is expected that Heating, Ventilation, and Air Conditioning (HVAC) systems will be provided so that the space can be maintained at an appropriate temperature (refer to ASHRAE [13-14] or MIL-STD-1472G [3] for guidance on HVAC and appropriate temperature ranges). When designing the room layout, the location of HVAC vents relative to operator positions should be considered to ensure that hot or cold air discharges are not directed on personnel.
- e. **Lighting.** The arrangement of lighting fixtures within the space relative to operator positions should be considered in the context of the tasks that the operators will be expected to perform at each position. Table XXII of MIL-STD-1472G [3] provides guidance regarding the level of illumination required for a variety of work areas and task types.
- f. **Ship Motion.** The effects of ship motion should be considered in the design of the room layout; for example, studies (e.g. [15]) have shown that workstations for standing personnel should be aligned perpendicular to the largest motions in the plane of the deck. Since the largest motions are generally in the roll axis, this means that standing workstations (e.g., chart tables, stateboards) should be arranged so that personnel working at them are facing fore or aft.
- g. **Weapons Firing.** While this issue is not in the same category as the six items described earlier in this section, it can have significant safety impacts and should be specifically considered in this context. As described in Section 3.4.1, the general preference expressed by SMEs for the arrangement of consoles and operators was that they face forward whenever possible. However, for consoles and operators that have control over weapons firing, particularly for weapons that can be aimed relative to the ship's heading, this preference should in practicality be considered a requirement.

Refer to MIL-STD-1472G [3] and MIL-STD-882E [16] for further information regarding workplace safety.

#### 3.4.4 Security

To ensure that access to secure information in the space is appropriately controlled, security should be specifically considered in the design of the layout. Security concerns can be addressed through two primary factors of the layout design:

- a. **Control of access to the space.** From a room layout perspective, the simplest solution when dealing with security concerns is to control access to the space (i.e., only allow entry to personnel cleared to see everything in the space). Using this solution can still have some impact on the layout of the space itself, as it may be necessary to ensure that uncleared personnel are unable to see controlled information from the doorway of the space (when open). In this case, the location of the doorway(s) and the field of view into the room for an observer at the doorway(s) should be considered to ensure that no controlled information is visible within that field of view.
- b. **Control of visibility of secure information within the space.** If it is necessary or desired to allow personnel into the space who are not cleared to view certain information within the space, the location of this information within the layout should be considered so that control



of access to it can be maintained. For example, displays that contain secure information should be located so that they cannot be viewed from the ingress, egress, or traffic flow routes within the space that will be used by unauthorized personnel. The sources of secure information should also be modelled as part of the communications analysis to ensure that they are considered appropriately in the overall room layout. Additionally, equipment (e.g. temporary curtains) or procedural (e.g. turning off displays when unauthorized personnel are in the space) mitigations can be used to address security concerns for specific information; however, the impact of these mitigations on the continued operation of the space should be considered carefully before their implementation.

### 3.4.5 Design Trade-Offs

When making design trade-off decisions, a variety of factors related to each element (e.g., function, task, goal, or communication link) affected by the trade-off should be considered. The factors that are most important to the trade-off decision may vary depending on the elements involved; however, all relevant factors should be considered in the trade-off decision. The following list provides an overview of factors that may impact the design trade-off process:

- a. **Importance.** The overall importance of the top-level intended function of the space being supported by the element should be considered; it is likely that decreased performance on less important functions such as husbandry will be accepted, if required, to ensure effective support of key operational functions.
- b. **Criticality.** The criticality of the element to the success of the top-level intended function of the space should be considered, as the design of the space should generally be optimized for the elements that are absolutely essential for success in preference to the elements that are helpful but not critical.
- c. **Functional Associations.** The degree to which the element can impact the performance outcome of other elements should be considered; performance for elements that may impact many other elements should generally be optimized at the expense of elements with fewer associations. This is particularly important for communication links which may not be critical to any single function but can have a significant impact on the overall performance of the space by virtue of their less critical impact on many different functions.
- d. **Frequency.** The frequency of performance of the element should also be considered, as in most cases elements that are performed frequently should be prioritized over elements that are seldom required. However, this factor should never be considered in absence of an assessment of importance and/or criticality, as highly important or critical elements that are seldom required may still need to be prioritized over less important or critical elements that are performed often.
- e. **Duration.** The duration of performance of the element should also be considered, as it may be desirable to support elements that occur for longer durations over elements that only occur briefly. However, as with the consideration of frequency, the duration should not be considered without also considering the importance and/or criticality of the element.

It should be noted that this list is not exhaustive and other factors specific to a function, task, goal, or communication link may also be important to consider in the assessment of design trade-offs. For an example of how the various performance factors can be considered as design trade-offs, it is useful to examine maintenance accessibility, as maintenance is a support function required in all spaces that is likely to be considered in design trade-offs against the operational functions of the space.

In particular, as part of the design trade-off process, it is possible that layout designs will be considered that provide sub-optimal accessibility for one or more maintenance tasks in order to improve performance on operational functions or tasks. The primary considerations for determining the acceptability of this type of trade-off from a maintenance standpoint are the frequency and the importance of the affected maintenance tasks. Design solutions that significantly impact frequent or important maintenance tasks are unlikely to be desirable. Other criteria for assessing design trade-offs that involve maintenance accessibility include:

- a. the time required to carry out the maintenance task, and whether it will be increased or decreased as a result of the layout design under consideration;
- b. the potential impact(s) to ongoing operations while carrying out the maintenance task (if the task can be carried out with operations ongoing, it is desirable to minimize impact to operations); and
- c. the potential risk of not completing the maintenance task (and associated risk of equipment failure) if the accessibility challenges of the layout design are too great.

For all instances where design trade-offs may have a noticeable impact on the performance of the intended functions of the space, the performance factors and layout options considered in the trade-off process and the final design decision made should be recorded to support SME validation of design decisions.

### **3.5 Layout Evaluation**

According to STANAG 3994 [11], Verification is an assessment of the degree to which the system and its components meets the design specifications as they were formulated as a basis for the design, while Validation (also known as Acceptance) is concerned with how well the system meets the actual needs of the end users in operational conditions.

Inputs to Verification and Validation typically include a large number of aspects; with respect to the V&V of compartment layout design the following factors, when applicable, should be considered:

- a. SME Inputs;
- b. HF Standards;
- c. Style Guide;
- d. Functional Specifications;

- e. Performance Specifications;
- f. Training Design;
- g. Manning Concept; and
- h. Procedures.

Verification and Validation sub-tasks include:

- a. **Plan Tests.** Although verification starts in the requirements process with the identification of acceptance criteria, detailed verification tests can only be developed when the design is firm. Validation is performed in a largely operational environment, although simulation is increasingly used. Verification and validation testing both need to be economical, with an aim to detect problems at as early a stage as possible at lowest cost. The test plans need to specify methods and tools, the acceptance criteria and the action taken if non-conformances are found; and
- b. **Conduct Tests.** Tests are conducted and the results are managed. Traceability needs to be maintained back to the overall requirements.

Specific considerations for verification and validation of room layouts are further detailed in Sections 3.5.1 and 3.5.2, below.

### 3.5.1 Verification

In the case of room layout, the design specifications that must be met include the communication requirements identified as a result of the analysis process described in Section 3.3. To assess the degree to which the notional layouts meet these requirements, they should ideally be entered into a modelling and simulation tool like LOCATE<sup>2</sup> or VNCEP<sup>3</sup> (Virtual Navigation and Collaboration Experimentation Platform) that allows for relative comparisons between the layouts.

If there is an immersive 3D capability with the tool then SMEs will also be able provide some initial evaluation of how the notional layouts would perform for them from their seated or standing positions within the layout (refer to Section 3.5.2 for further details on layout evaluation). This type of environment allows for an iterative design cycle to occur, allowing for rapid manipulation of the notional layouts and a ready comparison of the impact of the changes.

In addition to the recommended modelling and simulation approach to support verification of the layout in terms of the communication requirements, the following questions should also be considered:

---

<sup>2</sup> LOCATE is a DRDC tool that supports qualitative assessment of workspace communication quality within four domains: auditory, distance (or movement), tactile (or reach), and visual.

<sup>3</sup> VNCEP is a DRDC generic experimentation platform that provides a configurable capability to visualize proposed room layouts and interactively update them during SME sessions. The extensible scripting interface of VNCEP also supports the calculation of measures of communication effectiveness.

- a. Were appropriate SMEs consulted throughout the room layout process?
- b. Requirements and Assumptions:
  - i. Were the appropriate references (SOR, CONOPS, etc) used in identifying the intended functions of the space?
  - ii. Was a room size identified? If not, is the layout process being used to help specify a required room size?
  - iii. If a room size was identified, were the applicable construction features identified?
  - iv. Was a manning concept for the space recorded?
  - v. Were all operational conditions considered in the manning concept?
  - vi. Was the required equipment identified?
  - vii. Was the physical size/shape recorded for each piece of equipment?
  - viii. Were the maintenance requirements recorded for each piece of equipment?
  - ix. Were the ingress/egress requirements of the space identified?
  - x. Was an appropriate anthropometric data set selected?
  - xi. Were the requirements and assumptions validated with SMEs?
- c. Work Analysis:
  - i. Were the communications required for each intended function identified?
  - ii. Was the equipment required for each intended function identified?
  - iii. Was the storage space required for each intended function identified?
  - iv. Were the support functions of the space considered in the work analysis?
  - v. Was the work analysis validated with SMEs?
- d. Communications Analysis:
  - i. Were appropriate communication types identified for use in the communications analysis?
  - ii. Were angular and distance constraints identified for each communication type?

- iii. Was an appropriate measure of communication importance identified for use in the communications analysis?
  - iv. Was a source and a receiver identified for each communication required in the space?
  - v. Was a communication type identified for each communication required in the space?
  - vi. Was a measure of importance identified for each communication required in the space?
  - vii. Were the effects of ambient noise considered in the communications analysis?
  - viii. Was the communications analysis validated with SMEs?
- e. Layout Development:
- i. Were appropriate notional layouts developed based on the requirements of the space?
  - ii. Were ingress, egress, and traffic flow routes within the space considered in the notional layouts?
  - iii. Were maintenance accessibility requirements considered in the notional layouts?
  - iv. Was the required equipment in the space arranged to facilitate maintenance?
  - v. Were workplace safety concerns considered in the notional layouts?
  - vi. Were security concerns considered in the notional layouts?
  - vii. Were design trade-offs made in creating the notional layouts identified and recorded?

Along with the relative optimization comparison from modelling and simulation tools, and in part based on the validation questions above, a list of the tangible and intangible pros and cons should be established for each layout. This will allow SMEs to select the most appropriate layout, taking into account all relevant design trade-offs, design metrics, limitations of design, and design constraints. This will also provide the opportunity for SMEs to understand the implications the layout will have on task performance and potentially address items through procedural modifications prior or work allocation before they are faced with a live work event.

### **3.5.2 Validation**

Because validation is concerned with how well the system meets the actual needs of the end users in operational conditions, the layout evaluation process will require SME participation. The evaluations should include operators from all levels of experience that are anticipated to carry out

the work within the space. The use of only the most senior of the planned operators in each space will not provide the necessary feedback on the positioning of the equipment of other operators in relation to the junior operators. The layout evaluation should include:

- a. Comparison of test layouts using an empirical measure of communication effectiveness for each layout;
- b. Sensitivity analysis of the communication metrics;
- c. Structured walkthroughs, either virtual or physical mock-up, including the use of scenarios or vignettes to initiate discussion; and
- d. Discussion of design trade-offs.

## **4 Design Process Verification Guidelines**

---

### **4.1 Intent**

The intent of this Section is to provide additional details about the process described in Section 3 that will allow an evaluator to assess whether the process was followed appropriately and whether the developed layout meets the high level guidelines described in Section 1. Much of the information is related to the verification questions identified in Section 3.5.1 and should assist in answering them. This Section includes compartment-specific information where applicable.

### **4.2 Analysis**

Analysis verification is intended to ensure a complete set of analyses has been conducted. The contractor should be capable of demonstrating, against scenarios or vignettes, that all required functions within the compartment being designed have been considered in the analysis. There will be a requirement for the RCN to provide appropriate SMEs and HFE practitioners to confirm the analysis is complete.

Determining the number and type of SMEs a contractor should consult for Human Factors related projects is not governed by hard and fast rules. The type of SMEs used should be representative of all types of operators (i.e., ranks, MOSIDs, QLs, experience levels) that will be involved in the space or function. The numbers are typically tailored given the nature of design problem, and normally increase as the criticality of usability, or the mission-critical use of a system, increases.

There is little industry guidance on this topic; however, we can look to research done regarding Heuristic evaluations, a technique aimed at finding usability problems, to be able to position a reasonable estimate. Jakob Nielsen, an industry leading thinker regarding usability and Heuristic evaluations, contends that through his extensive experience that consulting one person is limiting as one person will never be able to represent all perspectives (i.e., find all the usability problems) [17]. As different SMEs will represent similar but distinct perspectives, it is reasonable to contend that effectiveness will improve by involving multiple SMEs. Through his analysis of unique usability problems reported, he recommends that three to five SMEs will provide the bulk of the information, with more SMEs providing less and less novel information, thus increasing the cost with little additional benefit. Nielson contends that the numbers of SME should be increased as the criticality of the system increases.

It should be noted that because Heuristic evaluations are used in assessing specific functions, when applying the recommended number of SMEs for Heuristic evaluations to determine a recommended number of SMEs required as part of layout design, the number of SMEs required should be determined per operator position or per function being carried out in a space.

## **4.2.1 Requirements and Assumptions**

The intent of this section is to provide additional information to assist the RCN in assessing whether the contractor has developed and is using a complete set of requirements and assumptions.

### **4.2.1.1 Reference Documents**

The CSC Statement of Requirement calls out ISO 8468:2007 [18] as an industry standard guidance document for the creation of bridge layouts. The American Bureau of Shipping (ABS) guidance document [19] on bridge design also provides useful information in this regard. Both of these documents should be used in support of the aims in SOLAS Chapter V Regulation 15 [2]. However, as all of these documents are specific to non-military vessels, the general guidance provided is applicable but the detailed design suggestions must be adapted for the military environment to take into account issues described in this document.

### **4.2.1.2 Intended Functions**

The purpose of identifying and recording the top-level intended functions of the space is to ensure that all desired capabilities in the space are considered in the design of the room layout. These functions therefore need to be expressed in sufficient detail that all desired capability is captured in a manner that can be validated by RCN SMEs. It should be noted, however, that the intended functions as described here serve primarily as the starting point for a more detailed work analysis process, so it is not necessary to define them in any further detail than is required to express the desired capabilities of the space. For example, an intended function such as “Conduct warfighting operations” may not provide the necessary level of detail to capture the desired capability, but expressing it as “Conduct underwater warfare operations”, “Conduct above-water warfare operations”, and “Conduct surface warfare operations” may be sufficient. An excellent starting point for the operations room functions is the Combat System Requirements listed in the SOR. The importance of ensuring the functions are fully captured can be explained in examples of intended functions expressed by RCN SMEs that were not considered during the design of the Canadian Patrol Frigate (CPF) and have recently caused manning and operating issues:

- Provide ship-wide IT support (likely to be a function of the CCR);
- Provide support for Task Group command (function of Ops room and CCR); and
- Provide support for conducting Unmanned Aerial Vehicle (UAV) operations (likely to be a function of or related to the Ops room).

It should be noted specifically at this point that the identification of intended functions for the bridge should also consider any functions that will be performed on the bridge wings or the visual communications station.



#### 4.2.1.3 Room Size and Features

It should only be acceptable not to identify a room size under the requirements and assumptions if the intent is for the contractor to use their room layout design to suggest the size and shape of the room required.

If the room size is known, all applicable factors discussed in Section 3.3.1 Item c (i.e., size, shape, and construction features) should be included in the recorded requirements and assumptions. Additionally, the material on room size should include some consideration of space provision for future growth; for land based control rooms, a standard practice is to add 20% space for expansion. Although this may not be practical in the design of a compartment in CSC, the contractor should be expected to discuss the design considered for additional functions or equipment within a space.

#### 4.2.1.4 Manning Concept

As described in Section 3.3.1 Item d, the recorded manning concept of the space should consider the variability in manning level with operational condition; for example:

- **Bridge.** The bridge of a warship is extremely dynamic and must be designed to accommodate a varying number of operators depending on the operational conditions; during normal operations there may be between 4 and 6 operators whereas during irregular conditions, such as a Replenishment At Sea (RAS) or Action Stations, there could be upward of 15 operators.
- **Operations Room.** The manning of the operations room is less dynamic than the bridge; however it must be designed to accommodate a varying number of operators depending on the readiness posture of the ship during different operational conditions.
- **Communications Control Room.** The manning of the CCR is relatively static. All conditions of operation must still be considered as the abnormal state may increase the manning depending on whether trouble shooting and/or maintenance is to be conducted in the CCR.
- **Machinery Control Room.** The MCR is extremely dynamic and must be designed to accommodate a varying number of operators depending on the operational conditions; during normal operations there may be between 2 and 5 operators whereas during irregular and emergency conditions, such as Action Stations or Emergency Stations, there could be upward of 10 operators – especially if the damage control headquarters is collocated with the MCR.

The recorded manning concept for each space should include a list of the operators that will be in each space during each operational condition.

#### 4.2.1.5 Equipment

The recorded assumptions should also include a list of all equipment required for each space; Tables 1 and 2 provide sample equipment lists for the bridge, ops room, CCR, and MCR. These lists are not exhaustive and will be affected by the system / equipment selections made by the contractor. SMEs must be involved in the development of complete lists prior to their use in

analysis and subsequent layout design. Note that any equipment and displays that will be required on the bridge wings should be included in the equipment list for the bridge.

The equipment listed in Table 1 and Table 2 may require physical access for control purposes or visual and/or auditory communication linkages or both. These links should be identified as part of the work analysis (Section 3.3.2) and communications analysis (Section 3.3.3).

*Table 1: Sample Bridge and Ops Room Equipment Lists.*

<b>Bridge Equipment</b>	<b>Ops Room Equipment</b>
Battle Damage Control System	Battle Damage Control System
Bridge stateboard	CCTV
Bridge weapons firing controls	Clock
CCTV	Command and control system (CCS)
Centerline azimuth / pelorus	Communication terminals (SHINCOM)
Chart table with instruments	Communications EMCON panel
Clock	Echo sounder readout
Command and control system (CCS)	ECM remote control panel
Communications (SHINCOM)	ECPINS / WECDIS / AIS
Communications stateboard	Electro Optic Sensors
Depth indicator	Gyro compass select switch
Echo sounder	Gyro repeat – ships course indicator
ECM controls	Helicopter status
ECM status panel	Helm / actual rudder angle readout
ECPINS or WECDIS	IFF controls
Electro Optic Sensors	Inclinometer
Emergency stop controls	Integrated Platform Management System
GPS panel / controls	Link equipment
Gyro repeat	Loud speakers
Helicopter status panel	Main radar control panels (if required)
Inertial navigation display	Mission fit radios
Integrated Platform Management System	Ordered / actual shaft speed indicator
Magnetic compass	Printers – bathymetric, GCCS, ...
Navigation lights control panel	Radiation Blanking Control panel
Navigation radar display / ARPA / AIS	Radiation control unit
Ordered and actual shaft speed	Secondary Gun System
Rate of turn indicator	Sonobuoy processing units (if required)
Rudder angle indicator	Sound powered phone
Search light controls	Speed log
Secondary Gun System	Stateboards
Speed / pitch indicator	Weapon veto panel
Speed log	Weapons remote control panels

Bridge Equipment	Ops Room Equipment
Steering control; manual and automatic Underwater telephone VHF Radio Weapons veto panel Whistle control Wind indicator Window wiper and washer controls	Weapons test panels Wind indicator

*Table 2: Sample CCR and MCR Equipment Lists.*

CCR Equipment	MCR Equipment
Communication terminals (SHINCOM) EMCON status indicator Ship's head indicator / gyro repeats Stateboards Transceivers	Battle Damage Control System CCTV Communication terminals (SHINCOM) Clock DC Console Integrated Platform Management System Inclinometer Ordered / actual shaft speed indicator Ship's head indicator / gyro repeat Citadel pressure / Manometer Secondary Steering Ship's Broadcast Speed log Stateboards

#### 4.2.1.6 Ingress and Egress

The ingress and egress requirements of each space will need to be identified. This will require input from the RCN, which could be provided either as performance requirements (e.g., the design of the space must allow evacuation of all personnel within 15 seconds) or as design specifications (e.g., the space must have a minimum of two separate entrances/exits, each operator must have at least two independent egress routes). In general, performance requirements allow the contractor more flexibility in the design of the space, but require greater effort and higher fidelity prototypes to validate.

#### 4.2.1.7 Anthropometric Data Sources

Selecting the appropriate anthropometric survey is important to ensure the best accommodation of a specific population. Human variability can be observed depending on the age, sex, ethnicity, and occupation of the source population. Also, some consideration should be given to the age of

the data as population change over time due to secular trend. Anthropometric data can be found in the following:

- 1997 Anthropometric Survey of the Land Forces
  - ♦ 140 traditional two-dimensional measures, as well as 2D and 3D images; 56 derived measures
  - ♦ 708 randomly selected regular force soldiers (243 women and 465 men)
- 1988 Anthropometric Survey of U.S. Army Personnel (NATICK TR-89/044)
  - ♦ 132 traditional two-dimensional measures and 60 derived dimensions calculated by adding and subtracting standard measures
  - ♦ Measures are now a military generation old (>22 years) - demographics of aircrew personnel have changed
- 1988 Anthropometric Survey of U.S. Army Personnel (NATICK TR-91/040) (Army Pilots)
  - ♦ 132 traditional two-dimensional measures and 60 derived dimensions calculated by adding and subtracting standard measures
  - ♦ Measures are now a military generation old (>22 years) - demographics of aircrew personnel have changed
- 1985 Anthropometric Survey of Canadian Forces Aircrew
  - ♦ Male aircrew only; 387 pilots and 132 navigators representing 30% of the total CF aircrew population and 30-35 % sample size for each aircraft category (helicopters, jets and trainers, multi-engine)
  - ♦ Measures are now a military generation old (>22 years) - demographics of aircrew personnel have changed
- MIL-STD-1472G, Appendix B, Anthropometric Values
  - ♦ Requirements call for the application of NATICK Technical reports, TR-89/044 (Army), TR-91/040 (Army Pilots) (1998)
  - ♦ 91 measures presented as summary statistics (5th percentile and 95th percentile female)
  - ♦ Numbers translated from mm in NATICK surveys to cm and rounded to first decimal place
  - ♦ Measures are now a military generation old (>22 years) - demographics of aircrew personnel have changed

The appropriate anthropometric survey needs to be selected for the design problems faced by the CSC project. It is suggested that the 1997 Anthropometric Survey of the Land Forces may be the most appropriate currently available anthropometric data applicable to Canadian Navy applications. However, it should be noted that 2012 Canadian Forces Anthropometric Survey (CFAS) collection phase is completed; gathering anthropometric measurements of over 2200+ CF personnel constituting a representative and proportional sample of all three services across the country. Data validation as well as tool development for data visualization (and some analysis) is underway. The CFAS is intended to replace the 1985 Anthropometric Survey of Canadian Forces

Aircrew and 1997 Anthropometric Survey of the Land Forces with an updated set of unencumbered body dimensions as well as state-of-the art 3D models able to contribute to continued studies of encumbered (clothed) anthropometry. The release of the preliminary CFAS validated data set, visualization and analysis tool, and report is expected to be delivered to all three services by March 2014.

The selection of the appropriate survey could be done by the Project Management Office (PMO) and identified as a requirement in the requirements specification or the contractor could be required to select an appropriate survey, subject to approval by the RCN. An example of a requirement dictating which survey must be used for a particular design problem can be found in MIL-STD-1472 G, Section 4.4.4 Accommodation [3], which states that the “Army shall use the anthropometric data found in NATICK TR-89/044 Anthropometric Survey of U.S. Army Personnel methods and summary statistics, and NATICK TR-91/040 Army Personnel Pilot Summary Statistics.”

For further information and considerations related to the use of the selected anthropometric data, refer to Section 4.3.2.1.

#### 4.2.2 Work Analysis

The following are a set of potential questions that could be posed to the contractor to assist in validating the work analysis conducted to support layout design:

- **Analysis Type.** What type of work analysis is being performed by the contractor? In general, any well-accepted form of work analysis (such as those listed in Section 3.3.2) should produce appropriate results for use in layout design. The experience of the authors has shown that HGA has some advantages that make it well-suited to support layout design work; the most significant of these is the flexibility of the analysis. Because HGA identifies and decomposes all goals before any goal is assigned to any operator, it allows for changes in the manning concept of the space without significant re-work of the analysis (i.e., the goal hierarchy itself will not need to be revised). Additionally, because HGA uses the goal as its descriptive unit at all levels of decomposition, the level of decomposition can be tailored to the intended application of the analysis; for the purposes of capturing communication requirements, this provides much greater flexibility than a traditional Task or Function analysis.
- **Intended Functions.** Did the contractor use the intended functions identified as part of the requirements and assumptions? Was the decomposition of the intended functions based on scenarios and vignettes that have been approved by the crown? For intended functions that are new or operationally unfamiliar to the RCN (e.g. naval fire support or UAV operations), did the contractor seek out appropriate SMEs or make valid assumptions to support their analysis? It should be noted that in these cases, appropriate SMEs may need to be drawn from other navies or armed force branches that do have experience with the intended function being analysed.
- **Watch Turnover.** Were issues associated with long-term or continuous (i.e. watchstanding) tasks such as watch turnover considered in the work analysis? These tasks need to be specifically identified in the work analysis as the communications and watch turnover

processes required may have a substantial impact on the ideal layout of the space, particularly if the watch turnover takes a significant amount of time.

Work analysis for all spaces should consider whether any operator will require access to the entrances/exits of the space to accomplish any of their tasks. Additionally, work analysis for the bridge functions should also specifically consider whether the operators require access to the bridge wings or the visual communications station.

Critical to the development of a communication is the importance of the function, goal, or task that is being supported by the communication. If the function is not important the weight given to the supporting communication links should carry less weight in the design of the space; whereas communications that support critical functions should be given more importance in the design.

The most direct way to gather SME ratings of importance, frequency, acceptability, agreement, knowledge of action, priority etc. for functions, tasks, or goals is to use survey or interview techniques. There are many techniques available and practitioners may have a particular preference. However, generally speaking, for small groups, a focus group technique may be appropriate, while a questionnaire may be more applicable for a larger group. Regardless of the method, some effort should be made to ensure questions are unambiguous and unbiased and that they prompt the users to answer in a consistent manner (i.e., response categories are well defined and easy to understand). One approach that has been found useful in previous layout design projects is to use 5 point, or 7 point, Likert scale response categories to bound SME responses. Some examples of Likert scales [20] are provided below:

#### Importance

- 1 – Not at all important
- 2 – Low importance
- 3 – Slightly important
- 4 – Neutral
- 5 – Moderately important
- 6 – Very important
- 7 – Extremely important

#### Frequency

- 1 – Never
- 2 – Rarely
- 3 – Sometimes
- 4 – Often
- 5 – Always

Or

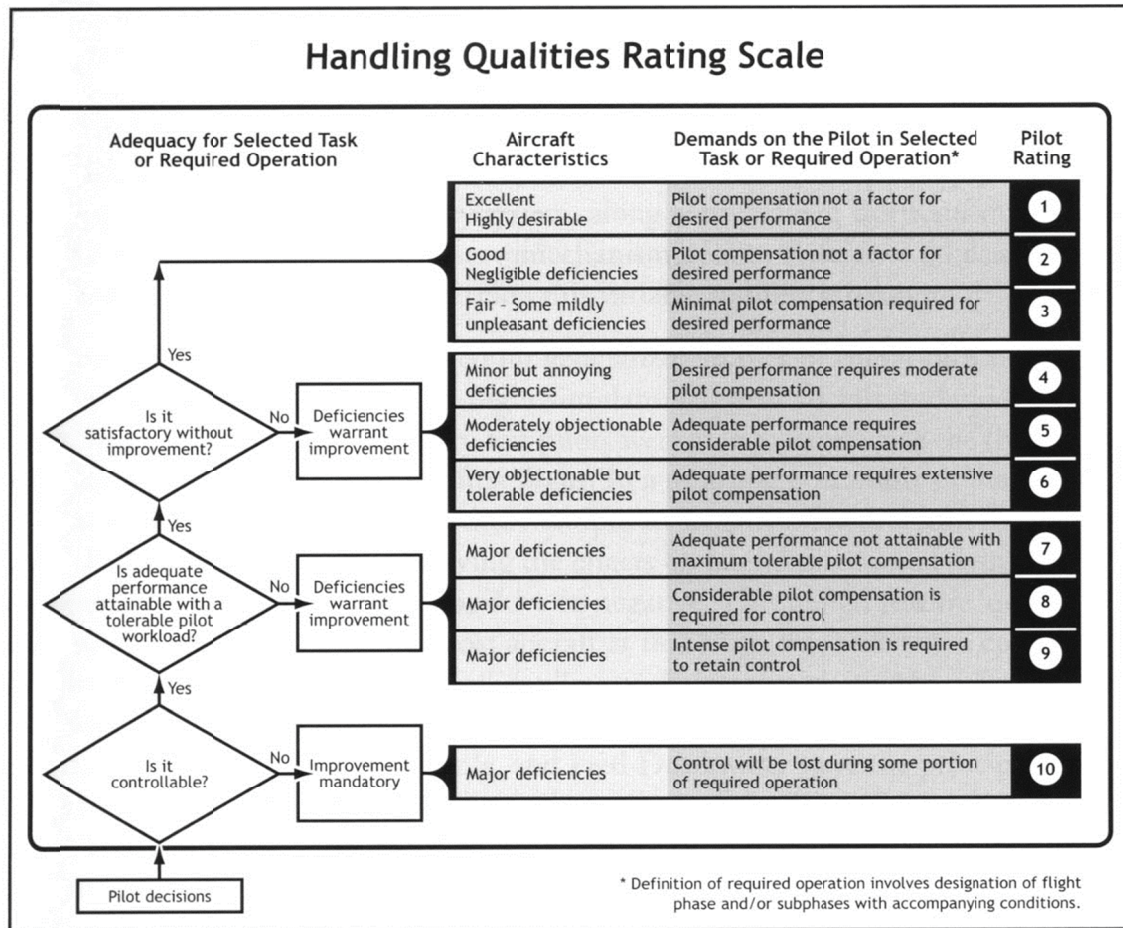
- 1 – Never
- 2 – Rarely
- 3 – Occasionally
- 4 – A moderate amount
- 5 – A great deal

#### Acceptability

- 1 – Totally Unacceptable
- 2 – Unacceptable
- 3 – Slightly Unacceptable
- 4 – Neutral
- 5 – Slightly Acceptable
- 6 – Acceptable
- 7 – Perfectly Acceptable

Other practitioners have chosen to adapt other rating scales specifically to address research questions. One example is the Honeywell modification of the Cooper-Harper [21] rating scale. The original Cooper-Harper scale, shown in Figure 4, originated in the aerospace domain for rating the handling characteristics of aircraft, and is based on three main questions that slot any aircraft into one of four main groupings based on the demand imposed on the pilot. If the answer to the first question is ‘YES’, the response leads across to a category that is a single solution with the highest demand rating. If the answer is ‘NO’, the scale leads up to more questions which will eventually lead to a major category with three possibilities. As can be seen there are a total of 10 possible ratings.





*Figure 4: Cooper-Harper Rating Scale.*

Honeywell adapted this rating scale, leveraging the decision-tree structure to assess overall task workload [22]. Others have adapted this type of decision-tree scale to suit other applications. Should a practitioner desire, they could choose to develop and validate modifications to the Cooper-Harper specific to rating the importance of functions, tasks, or goals. For example, instead of asking questions related to the handling qualities of an aircraft, the scale could be used to ask questions about how critical the goal/function/task is in supporting mission effectiveness. The question at each decision point (diamonds in Figure 4) would then be related to the impact of that goal on mission effectiveness. Instead of mission effectiveness, impacts on safety or on human performance could also be considered. Experience with adapting these types of scales has shown that validation by SMEs is required to ensure each decision point is appropriate and not open to misinterpretation and that responses or demand statements are unambiguous and unbiased.

Whether adapted Cooper-Harper scales or another method is used for the development of goal/function/task importance ratings, it can be seen that the SME input associated with work analysis can and should be very involved if the analysis is done to a sufficient level of detail.



### 4.2.3 Communications Analysis

The intent of this section is to provide additional information to assist the RCN in determining whether the contractor conducted a complete and thorough communications analysis. The following subsections address communication types and metrics in support of compartment specific layout design.

#### 4.2.3.1 Communication Types

The contractor must identify a number of communications types in order to populate a communication model or conduct link analysis. HFE practitioners should review the contractor's communication types to ensure they are robust enough to capture the complexity of communications demands found on the bridge and in the CCR, MCR, and operations room.

Operator-operator communication types that have been found useful in previous layout analyses, as used in the Control Space Optimization paper [24], include:

- **Supervise.** This link type corresponds to the specific relationship between a supervisor and anyone they are required to supervise. For command and control rooms this link is determined by the ability for the appropriate operator to see the screen of the supervised personnel.
- **Direct.** This communication type corresponds to the communications between directors and their directed personnel. This link type represents the specific request for information, and specific response to those requests. The ability to effectively direct is determined by the ability of the person giving direction to see the face of the receiver, and the ability of the person receiving to hear the director (visual and auditory components). For this link type, the ability to direct drops off quickly beyond a particular distance (e.g., 4m); this distance should be determined by SMEs for each workspace. The greater the distance, the greater the volume required, and the greater the potential directing will become a distraction to others.
- **Collaborate.** This communication type corresponds to the requirement for operators to have discussions without disturbing or involving other operators. Collaboration allows operators to maintain attention on chats or emails at their workstations while conducting a conversation. For this link type, the ability to have a side conversation drops off quickly beyond a particular distance (e.g., 1.6m); to be determined by SME for each workspace. The greater the distance, the greater the volume required, and the greater the potential the collaboration conversation will become a distraction to others.
- **Discuss.** This link type represents the ability for an operator to have a discussion with another operator or operators. Like collaboration, discussions allow operators to maintain attention on chats or emails at their workstations while conducting a conversation. For this communication type, the ability to have a conversation drops off quickly beyond a particular distance (e.g., 3m); to be determined by SME for each workspace. The greater the distance, the greater the volume required, and the greater the potential the discussions will become a distraction to others – however with a discussion, unlike collaboration, being overheard is not a driving factor and the topic of discussion may be of benefit for others to hear.
- **Access.** This link type also represents the ability for an operator to have a discussion with another operator or operators; however, in this case there is no intent for operators to maintain

attention on chats or emails at their workstations. In other words, it is considered acceptable for them to move about the space in order to conduct their discussion. For this type of communication operators may walk to other operators in the conduct of their work (consider both absolute walking distance and the directness of the path). Operators may also be required to address issues outside the main workspace, therefore proximity to an entrance or planning room should also be considered. For this communication type, the ability to have a discussion drops off quickly beyond a particular distance (e.g., 6m); the acceptable proximity is to be determined by SME for each workspace. The greater the distance, the greater the time away from the workstation, and the greater the potential a discussion will distract from primary duties.

- **Get Attention.** This link type represents the ability for an operator to attract the attention of another operator. For this link type, there are two criteria that capture the ability to get attention. Typically, the ability to get attention is not dependent on angle for distances less than 2.5m, since the operators are in reach of each other. For distances greater than 2.5m, however, the ability to get attention is generally limited to the field of view of the receiver in a nominal facing direction. The distance measure should be validated by SMEs for each workspace.

Operator-equipment communication types that have been found useful in previous layout analyses include:

- **Visual.** This communication type represents the ability for operators to receive visual information from a shared display. While there is no direct effect of distance regarding distraction of others, there are implications regarding screen size and font size required (i.e., MIL-STD-1472 [3] requirements).
- **Auditory.** This link type represents the ability for operators to receive auditory information. The distance between operators and an auditory source has implications regarding the attenuation of auditory sources. The angular placement of the source and receiver of auditory signals can also impact the salience of the auditory signal at the receiver. There are auditory models that can be consulted for more detailed information regarding auditory attenuations.
- **Access.** This link type represents the ability for operators to move about the space to access anything in the compartment, including exits, required to accomplish their task. This can be defined as a direct distance measure, as a distance required to travel (considering traffic flow routes in the space), or as a factor compared to an acceptable range. The factor assessment requires having first defined an acceptable distance the operators are willing to travel. In the case of the operations room where the majority of the operators are on headsets and are expected to be manning their workstations that distance may only be 3 or 4 metres. In the case of the CCR the operators may be content to walk up to 10 metres from their workstations as they tend to only need to respond to a phone call and need to be close enough to hear it ring and get to it in a reasonable time. With respect to access to the exit from the space, in the case of the CCR the on watch junior NAVCOM may be expected to report to the bridge or the operations room frequently during a watch and their distance to the door may be relevant.

The contractor may use communication types that differ from those listed in this section; however the crown must decide if the types being used are acceptable and adequate to capture the needs of the spaces being designed.

#### 4.2.3.2 Communication Metrics

##### Importance

The importance of each communication must be ranked as they support each individual function or goal. As described in Section 3.3.3, the primary factors that should be considered when determining the importance of a communication link are the expected frequency of the communication and the consequences of a failure in the communication. These two factors can be captured separately or combined into a single measure of importance, but both factors should be considered to ensure that the space can effectively support both ongoing and crisis response functions. When developing ratings based on these factors, it is advisable to use a validated 5 point Likert Scale or a scale similar to the 7 point scales shown in Section 4.2.2 to ensure all SMEs are responding using the same criteria.

##### Effectiveness

The effectiveness of each communication link in the layout being assessed must also be considered. As described in Section 3.3.3, the primary factors that are typically considered to impact communication effectiveness are the distance and angular alignment between the source and receiver of the link. Thus, numerical functions should be developed for each communication type that describe:

- the ideal angular measure and a degradation of communication effectiveness with angular displacement around the ideal; and
- the ideal distance and a degradation of communication effectiveness with distance.

There are a variety of functions that can be used to describe the effectiveness of communications based on angle and distance. Figure 5 shows a sample of a numerical function describing the effect of distance (left) and angle (right) on the effectiveness of a communication link.

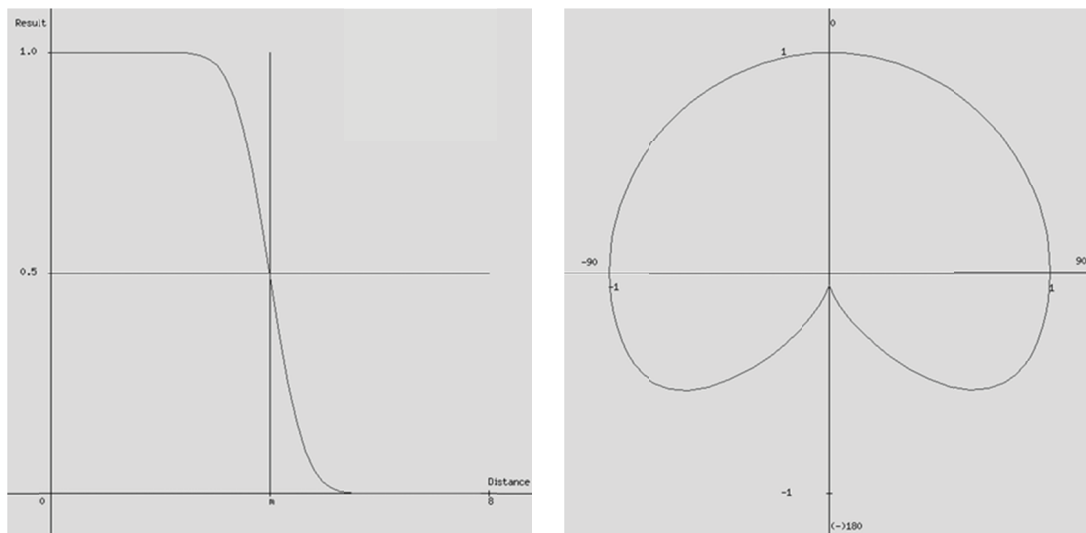


Figure 5: Sample Receiver Functions – Distance (RD) and Angular (RA).

The distance effect (left) shows that this communication type is highly effective to a distance of approximately 3m but the effectiveness drops off rapidly beyond this range. The angular effect (right) shows that the communication type is highly effective when the source is within approximately  $\pm 120^\circ$  of the receiver's facing direction but much less effective beyond that range. The distances and angles used for each of the communication types should be based on the requirements of the user community for the specific space and communication type, so they should be developed with input from RCN SMEs. Once completed, the numerical functions for each link type should be provided to the RCN for SME validation.

## **4.3 Layout Development**

The goal of the layout development process is to create a notional layout design that meets the requirements of the space and that can be subjected to a verification and validation process with SMEs. In general, the verification and validation process requires a model of the compartment as a starting point. This model can be as simple as a paper mock-up or as complex as a full-scale physical prototype. If the layout is being designed for a space that exists, the model should include as many of the construction features as possible; many of these will be constraints to communications and accessibility. In general, a more detailed and high fidelity model will generate more robust results in verification and validation, but requires more time and effort to create. Previous experience in layout design has shown that for the majority of the layout development process, computer-generated immersive 3D models provide an ideal compromise between cost and fidelity.

### **4.3.1 Communications**

To aid in the creation of a layout that effectively supports the required communications identified in the communications analysis, the descriptions of the communication links created in the analysis process should be included as part of the model. Ideally, this should be done based on mathematical functions for each communication link as described in Section 4.2.3.2. When inserting these functions into the model, it is recommended that the angular measures between the receiver and source be based on the position of the receiver when seated in their primary operating position facing their workstation.

In addition to the communication links, any constraints that may affect communications should also be factored into the mathematical computation of the communication links. This could include items such as: the overall floor plan, room heights, workstation/console design, engineering requirements such as cabling and structural components, or the ambient noise level in the space. The contractor should be able to indicate which concerns were considered and how each of these constraints was factored into the design.

### **4.3.2 Accessibility**

If an appropriate anthropometric data set has been identified for use in the design process (see Section 4.2.1.7), the primary concern in ensuring that physical accessibility considerations have been properly accounted for is the manner in which this anthropometric data was used in the design. The following subsection provides a brief overview of the key considerations regarding

the use of anthropometric data; further information on this topic can be found in Pheasant & Haslegrave [23], MIL-STD-1472G [3], and Sanders & McCormick [4].

#### **4.3.2.1 Use of Anthropometric Data**

In order to use anthropometric data in design, the design problem must be well understood (person, task, and environment). Understanding the design problem will help determine the relevant body characteristics integral to accommodate the user population.

Given that design problems are usually multivariate in nature, meaning there are several factors that may contribute to accommodation, and given that anthropometric measurements typically have weak correlation between each other, selecting the appropriate anthropometric dimensions to incorporate will have perhaps the most dramatic impact on the success of the design.

Consider a seated workstation; the following could be considered critical anthropometric dimensions for each aspect of the design problem:

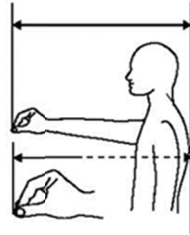
- Eye height sitting – impacts view over height and display layout;
- Elbow rest height (above seat pan) – impacts work surface height and control placement;
- Thumb tip reach – impacts control placement;
- Popliteal height – impacts seat adjustability;
- Thigh clearance – impacts clearance under work surface;
- Buttock-knee length – impacts clearance required under work surface;
- Buttock-popliteal length – impacts seatpan depth; and
- Functional leg length – impacts clearance required under workstation.

In practice, these measures need to be applied in conjunction with an understanding of the design problem to ensure anthropometric accommodations can be met.

- Design eye position.
  - ♦  $\text{Design eye position} = \text{seat height} + \text{eye height sitting}$
- Work surface (at elbow height)
  - ♦  $\text{Work surface} = \text{seat height} + \text{elbow height sitting}$
- Thigh clearance
  - ♦  $\text{Thigh clearance} = \text{seat height} + \text{thigh clearance} + \text{clothing and equipment}$
- Reach to controls
  - ♦  $\text{Reach to controls} = \text{thumb tip reach (from chair backrest)}$
- Knee/foot room
  - ♦  $\text{Knee room} = \text{buttock-popliteal length (from chair backrest)}$
  - ♦  $\text{Foot Room} = \text{functional leg length (from chair backrest)}$

## Selecting the appropriate type of measurement

Anthropometric measurements fall generally into two categories; structural and functional. Structural measures are taken with the body in a standard and still position (see Figure 6), while functional measures are taken when the body adopts working postures (see Figure 7). Selecting the appropriate type of anthropometric measurement will need to be determined on a case by case basis given the nature of the design problem.



*Figure 6: Structural Anthropometric Measurement.*



*Figure 7: Functional Anthropometric Measurement.*

## Special Considerations when applying Anthropometric Data

Anthropometric measurements are usually collected as semi-nude measures. This has implications if the measurements are used without taking into account clothing and protective equipment (e.g., work boots, helmet, gloves, night vision goggles, winter clothing). Every attempt should be made to identify the impact of clothing and ancillary equipment on the anthropometric measurements prior to design. For example, standing height may need to be adjusted to account for both work boot sole thickness and depth of protective headgear.

### 4.3.3 Safety

In general, validating that safety concerns have been appropriately addressed by the layout design will require input from appropriate SMEs; it is therefore recommended that System Safety and Health Hazards experts be involved in the review of the work analysis, communications analysis, and the layout design. The PMO should consider engaging D Safe G in reviewing the safety aspects of the compartment design.

One item from Section 3.4.3 that merits specific mention as a result of experience on previous ships is the climate control system of the operations room; it is understood from interviews with RCN personnel that the current operations room HVAC systems must discharge a significant amount of cold air to ensure that the equipment in the room is maintained at an appropriate temperature, and that the design of the vents is such that this cold air discharge is directed at least partially on the operators. This is counter to the requirements of MIL-STD-1472G [3] and results

in noticeable personnel discomfort; it should therefore be addressed in any new design of an operations room.

#### **4.3.4 Security**

To ensure that any security concerns for a space are appropriately addressed, the PMO should conduct an internal risk analysis as part of the layout evaluation to determine if the layout has adequately addressed or mitigated any security risks. These risks should be considered in terms of probability and consequences. It should be expected that where possible, the contractor's proposed layouts will make use of physical mitigations to account for security risks; for example, the existing frigate CCR uses a small "lobby"-type space inside the door to ensure that the field of view from the doorway does not allow visibility to any sensitive information or equipment.

However, given the nature of the spaces and the fact that operational needs may require sensitive information to be 'in the open' while maintainers or unauthorized personnel may be in the space, the RCN may have to adopt procedural precautions if there are no physical solutions that can adequately mitigate the risks. If such situations exist, the contractor should specifically identify areas where security concerns were identified by the RCN but were not able to be addressed as part of the layout design. Based on interviews with RCN personnel, one area where this may be likely to occur on the CSC is on the bridge if the new Command and Control System (CCS) is classified secret. If this is the case, the RCN should specifically ask the contractor what, if anything, was done in the design of the bridge layout to account for security concerns.

#### **4.3.5 Design Trade-Offs**

To ensure that design trade-offs between the various functions of the space have been appropriately considered and the correct layout decisions made, the PMO should require the contractor to record each important trade-off decision along with the rationale used in making it. These decisions and their associated rationale should be reviewed by RCN SMEs to ensure that the appropriate factors were considered and the correct decisions were made.

### **4.4 Layout Evaluation**

The evaluation of layout designs should include both verification activities and validation activities, as discussed in Section 3.5. The following subsections contain additional information related to these two types of evaluation activities.

#### **4.4.1 Verification**

The verification process is primarily a checklist style of activity; the contractor should be confirming and recording that all requirements were appropriately considered and that the layout design should support all performance goals identified during the analysis process. One effective way of conducting this activity is through the use of a compliance matrix; an example of how such a matrix could be prepared based on the guidelines in this document can be found in Annex A. The verification activities required within the PMO should primarily consist of reviewing a compliance matrix (or similar document) prepared by the contractor and to ensure that:



- the matrix captures all requirements and considerations; and
- all requirements and considerations identified in the matrix have been appropriately addressed.

This activity should include reviewing the support material identified by the contractor in the compliance matrix that demonstrates how each requirement or consideration was addressed.

#### 4.4.2 Validation

There are a variety of relevant factors that should be considered when planning and conducting the validation portion of layout evaluations. These factors include:

- **Evaluation plans.** The first step in conducting a layout evaluation should be preparing a plan that indicates what layouts will be tested, how they will be tested, how the results of the testing will be interpreted, and how the results and interpretation will be fed back into the design process. A key consideration within these plans is the integration of SMEs; i.e., how many and what kind of SMEs will be used, and how will their input be recorded and responded to. Due to the iterative nature of the process, several different evaluations, with increasing levels of detail and fidelity, should be conducted as the design matures. The PMO should expect a contractor to provide either a single evaluation plan indicating how evaluations will be conducted throughout the room layout process (describing each of the different planned evaluation types) or individual evaluation plans for each evaluation being conducted.
- **Prototype fidelity.** As the layout design progresses through iterations of the design process, the prototypes used to evaluate the layout design should increase in fidelity to match the maturity of the layout design. For example, it may be sufficient to assess early notional layouts using simple paper mock-ups or drawings, but the final layout design should ideally be validated using task-based, scenario driven evaluations with SMEs in full-scale physical mock-up of the room. Other prototyping techniques, such as 3D modeling, can be very useful in the intermediate stages of the design process.
- **Communication validation.** Because effective support of communications is a key driver of the layout design, it is generally recommended that an empirical measure of communication effectiveness be developed to support comparison between layout designs and assessment of design trade-offs. Experience on previous room layout projects has shown that an effective method is to develop a mathematical model that describes the quality of each communication link based on a source function, a receiver function, a link function, and a visibility function [24]. The source and receiver functions are based on angular and distance constraints, as described in Section 4.2.3.2, while the link function is used to capture usage information (e.g. number of lines of text used) where such information is available and the visibility function is used to describe the requirement for a line of sight between the source and receiver, if applicable. Because there are many communications of varying importance within a space, the quality factor of each link should also be weighted by the importance of the link. A measure of the overall quality of communications within a room can then be calculated based on the sum of the communication qualities and weights.
- **Sensitivity analysis.** Because there are many components that contribute to the overall measure of communication quality within a space, it is useful to examine the relative



importance of each component using a sensitivity analysis. For example, examining the sample receiver angular function shown on the right side of Figure 5, it can be seen that the receiver angular function drops off significantly for relative angles of greater than  $120^\circ$ . To conduct a sensitivity analysis on this parameter, the cut-off angle can be varied throughout the range of possible angles ( $0$ - $180^\circ$ ) to determine the sensitivity of the overall communication quality measure to the choice of cut-off angle. Similar variations can be performed on all parameters for the various component functions to help assess whether the layout design provides robust support to communications.

## 5 PMO Implications

---

Specific analysis must be conducted early in the design of major systems and equipment. The cost of rework becomes increasingly expensive if errors are found late in the development of equipment. The PMO must ensure that analysis is performed at the appropriate time to ensure that defects or poor designs can be addressed without unacceptable delays or increases to costs.

### 5.1 Intent

The intent of this Section is to provide a naval PMO with information regarding anticipated schedule and SME requirements associated with the process described in Section 3. This information is provided in sufficient detail to assist the PMO in the planning of timing and duration of availability required from RCN personnel to act as SMEs to provide inputs to the process and/or as evaluators to assess the contractor deliverables. Levels of effort and SME involvement are discussed based on the 3 main steps in layout generation from Figure 1.

### 5.2 High Level Requirements

In order to ensure that a contractor follows the process described in Section 3, several high-level requirements should be included in the SOR that specifically prescribe certain elements of the process. This section describes the reasons that these high level requirements should be included in the SOR.

Most importantly, there should be a high level requirement (or requirements) that specify the need for and the desired output of the room layout process. This requirement (or requirements) should include several key aspects:

- consideration of all the required capabilities of the space;
- consideration of all operating conditions that may be encountered in the space;
- consideration of all operators that will work in the space;
- consideration of all systems and equipment that will be installed and/or used in the space;
- a high-level performance measure (e.g., safety, efficiency, effectiveness).

The first two items above should ensure that the contractor identifies and analyses all the functions in the space, while the remainder ensure that the performance of the operators and equipment is considered.

#### 5.2.1 Communications

As communication is a key contributor of performance in a space, there should also be requirements that specifically call out the need to support communications within the space – both between operators and between operators and equipment. These requirements should also

require that communications with personnel and/or equipment outside the space be considered if the desired capabilities of the space require it.

The overall purpose of these requirements is to ensure that the contractor conducts an appropriate communications analysis and considers all required communications in their layout design.

### **5.2.2 Accessibility**

The appropriate range of population to accommodate needs to be specified. This should be done by the project and identified as a requirement in the requirements specification.

- An example of an anthropometric requirement can be found in MIL-STD-1472 G, Section 4.4.4 Accommodation [3]: “Equipment, systems, and subsystems shall be designed to accommodate the central 90 percent of the anticipated user population...”
- An interpretation of percentage accommodation requirements can be found in MIL-STD-1472 G, Section 3.3.5 Central 90 Percent Accommodation [3]: “...The distribution of the 10 percent not accommodated by the design including range of adjustment of system features should be evenly split between the smaller and larger portions of the population... <except when specified>”
- This interpretation is conventionally written into the requirement as: “Equipment, systems, and subsystems shall be designed to accommodate the 5th percentile female to 95th percentile male of the anticipated user population...” However, it is useful to note that such wording of a requirement has serious limitations and recent researches suggest the adoption of a multivariate approach for specifying the requirement such as the Effects of a Data Reduction Technique on Anthropometric Accommodation [25], Generation of Boundary Manikin Anthropometry [26], and Predefined Manikins to Support Consideration of Anthropometric Diversity by Product Designers [27].
- Consideration should be given to whether this population range is sufficient. For instance, if the segment of the population is not normally distributed (i.e., users work out with weights/ users self-select manual materials handling jobs) then increasing the range for critical anthropometric dimensions (e.g., shoulder breadth) may be prudent (e.g., 5th percentile female to 99th percentile male). Additionally, for potentially hazardous situations, as indicated in MIL-STD-1472 G, Section 5.8.3.2 Special situations [3]: “Where failure to accommodate the size or performance of personnel could result in a hazardous condition leading to personnel injury or equipment damage, the design for all physical factors (size, weight, reach, strength, and endurance) shall accommodate the central 99 percent of the target population including both genders.”

There should be a requirement in the requirements specification mandating the contractor identify the appropriate anthropometric dimensions, and type of anthropometric measurement, for each design problem, as the critical anthropometric dimensions may vary depending on the design problem and the accommodation sought.

Ingress, egress, and traffic flow routes within a space are important features of a space and have caused issues in previous room layout designs; therefore they may merit specific mention as part of the SOR to ensure that they are appropriately considered by the contractor.

Maintenance accessibility is a well-known issue and has a significant amount of material dedicated to it in MIL-STD-1472G [3]; it should also be specifically identified as a consideration for room layout in the SOR. Husbandry, while not as critical as maintenance, also has accessibility considerations and should be specifically identified as a requirement.

### **5.2.3 Safety**

Ensuring personnel safety is always an important consideration, and specific requirements should be included to oblige the contractor to account for workplace hazards and environmental considerations.

### **5.2.4 Security**

Security is a concern in any space that will involve work with sensitive information, so a requirement should be included to ensure that any security issues are specifically considered in the layout designs.

## **5.3 Analysis**

The Human Systems Integration and Human Factors Engineering support provided by contractors tends to be limited – it is not unusual for a large project to be support by a single Human Factors practitioner. Given this limited support the time to conduct analyses and produce useful result is generally longer than one would expect.

As per the guidance provided in NATO STANAG 3994 [11], there are several inputs to Work Analysis / System Analysis that the project staff may require prior to commencing any room layout design work. The project may need to provide high-level, performance based descriptions of the operational requirements; where Defence policy and strategy dictate operational requirements, the relevant policy and/or strategy documents must be identified. A CONOPS may also be required to outline future equipment operations and the vision for how the system will be staffed. In addition to the CONOPS and future staffing vision, information regarding the current system staff and procedures may be of benefit to communicate the context of use and some information regarding current task allocations and the range of ranks and specialties. Once this type of information is collected, the Work Analysis/ System Analysis will be better informed with information that will aid in the analysis of sub-tasks (e.g., link analysis).

### **5.3.1 Work Analysis**

The underlying purpose of work analysis is to support all HSI / HFE efforts for the project (such as Target Audience Description, training needs analysis and workload analysis); however in the case of supporting compartment layout generations the work analysis can be limited by the tasks or goals for each space and the number of operators for each space. This will still be a very large volume of work; for example, a very limited analysis of an MCR created 60 goals. Work analysis for the CPF operations room created 551 goals and when reanalyzed in support of HMCCS this number increased to 668 goals. Based on the scale of the bridge and the CCR, it is possible to extrapolate the level of effort and estimate that the bridge could have approximately 200 goals

and the CCR could be in the range of 40 to 50. This analysis will require SME support from the RCN with representation from all MOSIDs employed in the four compartments.

Overall the work analysis, for all 4 spaces, could take up to 9 months and require 3 to 4 weeks of dedicated SME support. The level of effort in person days could be as great as 500.

### **5.3.2 Communications Analysis**

Level of effort to complete the communications analysis is related to the work analysis and the type/volume of communications that is necessary to conduct the tasks or complete the goals. The communications analysis must take into account the communications between operators and the visual and auditory demands from sources such as displays, alarms and speakers. As part of the analysis, the type of communications (e.g., supervise, direct, discuss, collaborate, etc) must be defined and the frequency and importance of each communication link within the compartment must be determined.

Given the complexity of the analysis, the level of effort for the communications analysis of both the bridge and the operations room will be significant. For example, the analysis for the HMCCS operations room resulted in approximately 1200 communication links; identifying the communication type, frequency, and importance for each link individually is not overly time consuming, but the number of links results in a significant time commitment. The bridge has fewer operators; however, there are a large number of visual and auditory sources on the bridge and each must be considered in the communications analysis.

The expected time to conduct the communications analysis for both the operations room and the bridge would be approximately 3 months and would require significant input from domain experts from the navy (MOSIDs from each space would be required).

The MCR analysis would require less effort than the bridge and operations room. However, if Damage Control Headquarters (HQ1) is collocated in the MCR the effort would still be significant. It is expected this would take approximately 1 month for a team of 2 and several SME sessions.

The CCR is the least complicated space with the fewest operators and still fewer visual and auditory sources. The effort for the CCR communications analysis should take approximately two weeks and most likely require 2 SME sessions with 2 or 3 domain experts each to complete.

Overall the communications analysis, for all 4 spaces, could take up to 6 months and require 3 - 4 weeks of dedicated SME support. The level of effort in person days could be as great as 300.

## **5.4 Layout Development**

### **5.4.1 Notional Layouts**

The contractor should be able to create the notional layouts without significant SME involvement; however, it may be prudent for the contractor to provide preliminary layouts in 2-dimensional

format as confirmation that all properties of the compartment have been considered (operators, workstations, ancillary equipment and displays).

#### **5.4.2 Test Layouts**

The bulk of the layout analysis does not require SME involvement; the contractor should be iteratively analyzing several test layouts in order to optimize the communications and accessibility. Some PMO involvement may be required to confirm the algorithms being employed to calculate the effectiveness or efficiency of the communications.

This should take the contractor a total of 2 – 3 weeks of concerted HFE effort to develop potential test layouts for the four compartments. It would be reasonable to expect a contractor to take 4-6 calendar weeks to complete this if their HFE personnel are working on other aspects of the project.

### **5.5 Layout Evaluation**

SMEs should be presented well developed options with supporting documentation describing trade-offs made in the layout designs (e.g., where the effectiveness of certain communication links was reduced in order to increase others).

The RCN should try to involve as many SMEs as possible in the evaluation of the layouts. The contractor should be able to use virtual modelling to show the potential (test) layouts to SMEs on both coasts and in Ottawa. If the contractor is using a physical mock-up then the number of personnel evaluating each layout will be decreased however the feedback should be of slightly higher quality / fidelity.

If the contractor is using virtual modelling then it could be expected to take up to 2 weeks with each set of SMEs to review and evaluate the four compartments.

## **6 Conclusion**

---

This report contains guidance for the development of workspace layout for naval compartments that have complex communication and personnel interaction requirements. The compartments best served by the application of these guidelines are spaces with multiple operators and considerable or complex information requirements such as the operations room or the machinery control room. The intent of the guidelines is to provide the PMO with a method to ensure the contractor will consider all factors when designing specific compartments.

### **6.1 Use of Guidelines**

The use of guidelines to inform requirements is a practical method to ensure complex systems are designed and built to be effective and efficient once fielded. The use of guidelines and means of compliance (the compliance matrix at Annex A) have been employed in the aerospace industry for years to ensure the certification authorities can adequately assess the development and implementation of systems without being descriptive in the system design process.

These guidelines are focussed on the placement of operators and equipment in spaces with an emphasis on effectiveness related to communications, personnel movement (into, out of, and within a space), safety, and accessibility for maintenance and habitability.

### **6.2 Future work**

Follow on work to these guidelines can take two forms. The first could be the application of feedback from the use of the guidelines in order to improve the document. The second could be the adaption of these guidelines for other military applications or establishments that have similar demands on their operators as those in control spaces of a naval vessel.

## References

---

- [1] International Organization for Standardization, Ergonomic dressing of control centres, ISO 11064, 2000.
- [2] ATOMOS SOLAS IV Regulation V/15 Template – Retrofit and Newbuild, 13 October 2003.
- [3] Department of Defence Design Criteria Standard, Human Engineering, MIL-STD-1472G, 11 January 2012.
- [4] Sanders, M. & McCormick, E., Human Factors in Engineering and Design, McGraw-Hill, 1 January 1993.
- [5] International Organization for Standardization, Ergonomics of Human System Interaction, ISO 9241.
- [6] Department of Defence Handbook, Human Engineering Program Process and Procedures, MIL-HDBK-46885A, 17 May 1999.
- [7] Rasmussen, J., Information Processing and Human Machine Interaction: An Approach to Cognitive Engineering, North Holland, New York, 1986.
- [8] Vicente, K.J., Cognitive Work Analysis: Toward Safe, Productive, and Healthy Computer-Based Work, Lawrence Erlbaum Associates, Mahwah, NJ, 1999.
- [9] Hendy, K.C., Beevis, D., Lichacz, F. & Edwards, J. L., Analyzing the cognitive system from a perceptual control theory point of view, in M. D. McNeese & M. A. Vidulich (Eds.), Cognitive Systems Engineering in Military Aviation Environments: Avoiding Cogminutia Fragmentosa!, (pp. 201-250), Dayton, OH, 2002.
- [10] Wilson, J., & Corlett, N., Evaluation of Human Work, 3rd Edition, CRC Press, 2010.
- [11] NATO STANAG 3994, Application of Human Engineering to Advanced Aircrew Systems, 2007.
- [12] Ivergard, T. & Hunt, B., Handbook of Control Room Design and Regulations, A Perspective for the Future, Second Edition, 2009.
- [13] ASHRAE Standard 26 -- Mechanical Refrigeration and Air-Conditioning Installations Aboard Ship, ANSI/ASHRAE 26-2010.
- [14] ASHRAE Standard 55 -- Thermal Environmental Conditions for Human Occupancy, ANSI/ASHRAE 55-2010.
- [15] Bridger, R. S. & Crossland, P., Predicting Loss of Balance on Moving Platforms, in Contemporary Ergonomics, McCabe, P.T. (ed), 2004.



- [16] Department of Defence Standard Practice, System Safety, MIL-STD-882E, 11 May 2012.
- [17] Neilsen, J., How to Conduct a Heuristic Evaluation, <http://www.nngroup.com/articles/how-to-conduct-a-heuristic-evaluation/>, accessed 23 March 2012.
- [18] International Organization for Standardization, Ships and marine technology -- Ship's bridge layout and associated equipment -- Requirements and guidelines, ISO 8468, 2007.
- [19] American Bureau of Shipping, Guidance Notes on Ergonomic Design of Navigation Bridges, ABS Publication #119, Oct 2003.
- [20] Vagias, W. M., Likert-type scale response anchors, Clemson International Institute for Tourism & Research Development, Department of Parks, Recreation and Tourism Management, Clemson University, 2006.
- [21] Cooper, G. E. & Harper, R. P. Jr., The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities. NASA TN D-5153, 1969.
- [22] Gawron, V., Human Performance, Workload, and Situational Awareness Measures Handbook, CRC Press, 2008.
- [23] Pheasant, S. & Haslegrave, C., Bodyspace: Anthropometry, Ergonomics And The Design Of Work, Taylor & Francis, 2006.
- [24] Coates, C. & Perlin, M., Control Space Optimization. Presented at the 2009 14th International Ship Control Symposium, Ottawa, Canada, September 2009.
- [25] Meunier, P., Effects of a Data Reduction Technique on Anthropometric Accommodation, Proceedings of the Human Factors and Ergonomics Society 42<sup>nd</sup> Annual Meeting, 1998.
- [26] Young, K.S., Margerum, S., Abbe, B., Ferrer, M.A., Rajulu, S., Generation of Boundary Manikin Anthropometry, SAE 38<sup>th</sup> International Conference on Environmental Systems, 2008.
- [27] Hogberg, D., Case, K., Predefined Manikins to Support Consideration of Anthropometric Diversity by Product Designers, 2007.

## **Annex A   Example Compliance Matrix**

---

The example compliance matrix for the validation of the room layout design process can be found on the following 5 pages.

Layout Guidelines		Guideline Criteria	Complies Yes, No, N/A	Comment provide Reference and Section
Topic	Doc Section			
Analysis				
References	3.3.1	Were appropriate reference documents used to support the layout design?		Provide list of reference documents
Operating Conditions	3.3.1 a	Were normal operating conditions considered?		
		Were irregular operating conditions considered?		
		Were abnormal operating conditions considered?		
		Were emergency operating conditions considered?		
Intended Functions	3.3.1 b	Were the appropriate references (SOR, CONOPS, etc.) used in identifying the intended functions of the space?		Indicate which reference documents were used
		Were operational functions considered?		
		Were firefighting and damage control functions considered?		
		Were maintenance functions considered?		
		Were force generation functions considered?		
		Were evaluation and assessment functions considered?		
		Were husbandry functions considered?		
Room Size	3.3.1 c	Was the actual room size used?		
		If the actual room size was not used, was the layout process used to help specify a required room size?		
		If a room size was identified, were the applicable construction features identified?		
Manning Concept	3.3.1 d	Was a notional manning concept (or concepts) identified?		
		Were all operational conditions considered in the manning concept(s)?		
Equipment	3.3.1 e	Were workstations included in the analysis?		
		Were shared displays included in the analysis (e.g., large screen displays, stateboards)?		
		Was communication equipment included in the analysis?		
		Was any specific ancillary equipment included in the analysis?		
		Was the physical size/shape recorded for each piece of equipment?		
Ingress and Egress	3.3.1 f	Were the maintenance requirements recorded for each piece of equipment?		
		Were the ingress and regress requirements for the space specified?		

Layout Guidelines		Guideline Criteria	Complies Yes, No, N/A	Comment provide Reference and Section
Topic	Doc Section			
Anthropometric Data	3.3.1 g	Was an appropriate anthropometric data set selected?		
SME Input	3.3 and 4.2	Were the requirements and assumptions validated with appropriate SMEs?		Indicate number, type, and experience level of SMEs
		Was SME feedback incorporated into the requirements and assumptions?		
Work Analysis	3.3.2	Was a recognized methodology used for the work analysis?		
		Did DND review and accept the methodology?		
		Were all intended functions of the space considered in the work analysis?		
		Was frequency data collected for functions/ tasks?		
		Was importance data collected for functions/ tasks?		
		Were operational links between functions identified?		
		Were information flow and communications requirements identified?		
		Was support equipment identified as required for each function/ task?		
SME Input	3.3 and 4.2	Were storage space requirements identified?		
		Was the work analysis validated with appropriate SMEs?		Indicate number, type, and experience level of SMEs
Communication Analysis	3.3.3  3.3.3 a  3.3.3 c  3.3.3 b  3.3.3  3.3.3 a	How was SME feedback incorporated into the work analysis?		
		Did the communication analysis consider all information flow and communication requirements identified in the work analysis?		
		Were appropriate communication types identified for use in the communications analysis?		
		Were angular and distance constraints identified for each communication type?		
		Was an appropriate measure of communication importance identified for use in the communications analysis?		
		Was a source and a receiver identified for each communication required in the space?		
		Was a communication type identified for each communication required in the space?		

Layout Guidelines		Guideline Criteria	Complies Yes, No, N/A	Comment provide Reference and Section
Topic	Doc Section			
	3.3.3 b	Was a measure of importance identified for each communication required in the space?		
	3.3.3 d	Were the effects of ambient noise (masking and distraction) considered in the communications analysis?		
SME Input	3.3 and 4.2	Was the communication analysis validated with appropriate SMEs?		Indicate number, type, and experience level of SMEs
		How was SME feedback incorporated into the communication analysis?		
Layout Development				
Notional Layouts	3.4.1	Were appropriate inputs used as the basis of the notional layouts?		Provide a list of inputs
		Were the results of the communication analysis considered in the notional layouts?		
		Was consideration given to the direction that each operator will be facing relative to the ship’s orientation?		
		Were multiple notional layouts generated?		
Accessibility	3.3.1 g	Was the correct anthropometric data used in designing for accessibility?		
	3.3.1 e	Were accurate equipment sizes used in designing for accessibility?		
	3.4.2.1	Did accessibility considerations include ingress, egress, and traffic flow?		
		Regarding ingress, egress, and traffic flow; was the potential for distraction considered?		
		Regarding ingress, egress, and traffic flow; was access to exits considered?		
	3.4.2.2	Did accessibility considerations include maintenance access?		
		Was the location of maintenance action considered in the layout development?		
		Was the space required for maintainers considered in the layout development?		
Was the space required for maintenance tools and equipment considered in the layout development?				
Safety	3.4.3 a	Was consideration given to workplace hazards?		
	3.4.3 b	Was consideration given to workplace noise?		

Layout Guidelines		Guideline Criteria	Complies Yes, No, N/A	Comment provide Reference and Section
Topic	Doc Section			
	3.4.3 c	Was consideration given to workplace vibration?		
	3.4.3 d	Was consideration given to workplace climate?		
	3.4.3 e	Was consideration given to workplace lighting?		
	3.4.3 f	Was consideration given to ships motion?		
	3.4.3 g	Was consideration given to weapons firing?		
Security	3.4.4 a	Was the requirement for access control to spaces considered?		
	3.4.4 b	Was the requirement for visibility control of secure information considered?		
Design Trade-Offs	3.4.5	Were design trade-offs made in creating the notional layouts documented?		
SME Input	3.3 and 4.2	Were appropriate SMEs involved in the development of the notional layouts?		Indicate number, type, and experience level of SMEs
		How was SME feedback incorporated into the notional layouts?		
<b>Layout Evaluation</b>				
Verification	3.5.1	Were verification activities performed throughout the analysis and layout development process?		
Validation Inputs	3.5	Were HF standards referenced in the layout evaluations?		
		Was a style guide referenced in the layout evaluations?		
		Were functional specifications referenced in the layout evaluations?		
		Were performance specifications referenced in the layout evaluations?		
		Was training design considered in the layout evaluations?		
		Was a particular manning concept considered in the layout evaluations?		
		Were operating procedures referenced in the layout evaluations?		
Communication Validation	3.5.2 a	Were layouts validated using an empirical measure of communication effectiveness?		
	3.5.2 b	Was a sensitivity analysis performed on the communication metrics for each layout during validation?		
Layout Validation	3.5.2 c	Were structured walkthroughs (virtual or physical mock-up), conducted using scenarios, or vignettes, during layout validation?		

Layout Guidelines		Guideline Criteria	Complies Yes, No, N/A	Comment provide Reference and Section
Topic	Doc Section			
Design Trade-Offs	3.5.2 d	Were design trade-offs identified, assessed, and recorded for each layout during validation?		
SME Input	3.3 and 4.2	Were appropriate SMEs involved in the layout evaluations?		Indicate number, type, and experience level of SMEs
		How was SME feedback incorporated into the test layouts?		

## List of symbols/abbreviations/acronyms/initialisms

---

ABS	American Bureau of Shipping
CCR	Communications Control Room
CCS	Command and Control System
CFAS	Canadian Forces Anthropometric Survey
CO	Commanding Officer
CONOPS	Concept of Operations
CPF	Canadian Patrol Frigate
CSC	Canadian Surface Combatant
DRDC	Defence Research & Development Canada
HF	Human Factors
HFE	Human Factors Engineering
HGA	Hierarchical Goal Analysis
HSI	Human Systems Integration
HVAC	Heating, Ventilation, and Air Conditioning
HQ1	Damage Control Headquarters
ISO	International Organization for Standardization
MCR	Machinery Control Room
MFTA	Mission, Function, Task Analysis
MOSID	Military Occupation Specification Identification
NATO	North Atlantic Treaty Organization
ORO	Operations Room Officer
PMO	Project Management Office
PPE	Personal Protective Equipment
QL	Qualification Level
RAS	Replenishment At Sea
RCN	Royal Canadian Navy
SME	Subject Matter Expert
SOLAS	Safety of Life at Sea
SOR	Statement of Requirements
STANAG	Standardization Agreement
UAV	Unmanned Aerial Vehicle
VNCEP	Virtual Navigation and Collaboration Experimentation Platform
WDA	Work Domain Analysis



DOCUMENT CONTROL DATA		
(Security classification of title, body of abstract and indexing annotation must be entered when the overall document is classified)		
1. ORIGINATOR (The name and address of the organization preparing the document. Organizations for whom the document was prepared, e.g. Centre sponsoring a contractor's report, or tasking agency, are entered in section 8.)	2. SECURITY CLASSIFICATION (Overall security classification of the document including special warning terms if applicable.)	
Esterline   CMC Electronics Inc 415 Legget Drive, PO Box 13330 Ottawa, ON, Canada K2K 2B2	UNCLASSIFIED (NON-CONTROLLED GOODS) DMC A REVIEW: GCEC APRIL 2011	
3. TITLE (The complete document title as indicated on the title page. Its classification should be indicated by the appropriate abbreviation (S, C or U) in parentheses after the title.)		
Human Factors Analysis and Layout Guideline Development for the Canadian Surface Combatant (CSC) Project: Final Report		
4. AUTHORS (last name, followed by initials – ranks, titles, etc. not to be used)		
McKay, P.; Coates, C.; Stewart, A.; Perlin, M.		
5. DATE OF PUBLICATION (Month and year of publication of document.)	6a. NO. OF PAGES (Total containing information, including Annexes, Appendices, etc.)	6b. NO. OF REFS (Total cited in document.)
April 2013	75	27
7. DESCRIPTIVE NOTES (The category of the document, e.g. technical report, technical note or memorandum. If appropriate, enter the type of report, e.g. interim, progress, summary, annual or final. Give the inclusive dates when a specific reporting period is covered.)		
Contract Report		
8. SPONSORING ACTIVITY (The name of the department project office or laboratory sponsoring the research and development – include address.)		
Defence R&D Canada – Toronto 1133 Sheppard Avenue West P.O. Box 2000 Toronto, Ontario M3M 3B9		
9a. PROJECT OR GRANT NO. (If appropriate, the applicable research and development project or grant number under which the document was written. Please specify whether project or grant.)	9b. CONTRACT NO. (If appropriate, the applicable number under which the document was written.)	
10a. ORIGINATOR'S DOCUMENT NUMBER (The official document number by which the document is identified by the originating activity. This number must be unique to this document.)	10b. OTHER DOCUMENT NO(s). (Any other numbers which may be assigned this document either by the originator or by the sponsor.)	
N/A	DRDC Toronto CR 2013-043	
11. DOCUMENT AVAILABILITY (Any limitations on further dissemination of the document, other than those imposed by security classification.)		
UNLIMITED		
12. DOCUMENT ANNOUNCEMENT (Any limitation to the bibliographic announcement of this document. This will normally correspond to the Document Availability (11). However, where further distribution (beyond the audience specified in (11) is possible, a wider announcement audience may be selected.)		
UNLIMITED		

13. **ABSTRACT** (A brief and factual summary of the document. It may also appear elsewhere in the body of the document itself. It is highly desirable that the abstract of classified documents be unclassified. Each paragraph of the abstract shall begin with an indication of the security classification of the information in the paragraph (unless the document itself is unclassified) represented as (S), (C), (R), or (U). It is not necessary to include here abstracts in both official languages unless the text is bilingual.)

These guidelines have been developed under contract to the DRDC Toronto Human Systems Integration (HSI) Section in support of the Canadian Surface Combatant (CSC) project. The goal of the project was to provide the Royal Canadian Navy (RCN) with a set of guidelines on analysis, design, and verification processes for effective room, equipment, and workstation layout in the bridge, operations room, machinery control room (MCR), and communications control room (CCR) in the yet to be designed CSC. The guideline development drew upon experience in the design of control spaces for complex systems, from existing guidance documents, and from interviews with domain experts

Les lignes directrices du plan d'étage pour le projet Navire de combat canadien (NCC) ont été développées sous contrat avec la section d'intégration de Systèmes humaines de recherche et développement pour la défense Canada. L'objectif du contrat était de fournir à la Marine royale canadienne un ensemble de lignes directrices sur l'analyse, la conception et les processus de vérification du plan d'étage efficace, et de la distribution efficace de l'équipement et du poste de travail dans le pont, la salle d'opérations, la salle de contrôle des machines et la salle de contrôle des communications pour le navire du futur. L'élaboration de lignes directrices appliquait l'expérience dans la conception des espaces de contrôle pour les systèmes complexes, de documents d'orientation existants, et d'entretiens avec des experts du domaine.

14. **KEYWORDS, DESCRIPTORS or IDENTIFIERS** (Technically meaningful terms or short phrases that characterize a document and could be helpful in cataloguing the document. They should be selected so that no security classification is required. Identifiers, such as equipment model designation, trade name, military project code name, geographic location may also be included. If possible keywords should be selected from a published thesaurus, e.g. Thesaurus of Engineering and Scientific Terms (TEST) and that thesaurus identified. If it is not possible to select indexing terms which are Unclassified, the classification of each should be indicated as with the title.)

Layout guidelines; Human Factors; Canadian Surface Combatant